SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT

Preliminary Staff Report for

PROPOSED AMENDED RULE 1110.2 -- EMISSIONS FROM GASEOUS- AND LIQUID-FUELED INTERNAL COMBUSTION ENGINES

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EXECUTIVE SUMMARY

The South Coast Air Quality Management District's (AQMD) is the air pollution control agency for all of Orange County and the urban portions of Los Angeles, Riverside and San Bernardino counties. AQMD is responsible for controlling emissions primarily from stationary sources of air pollution.

Rule 1110.2 is the rule that regulates emissions of stationary and portable engines in AQMD. It was adopted in 1990 and last amended in 2005. There are two main reasons for amending the rule. First, AQMD enforcement staff has found through unannounced emission tests that stationary engines are out of compliance with their emissions limits about half the time, due to poor operating and maintenance procedures and inadequate monitoring required by the rule. Second, the Draft 2007 Air Quality Management Plan has found that additional emission reductions are needed to meet the more stringent federal ozone and particulate matter standards.

The proposed amendments will:

- Increase the monitoring requirements of the rule, to improve compliance;
- In the next three to five years, require stationary, non-emergency engines to meet emission standards equivalent to current Best Available Control Technology (BACT);
- Require new electrical generating engines to meet the same requirements as large central power plants; and
- Clarify the status of portable engines.

CHAPTER 1: BACKGROUND

SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT

The South Coast Air Quality Management District's (AQMD) is the air pollution control agency for all of Orange County and the urban portions of Los Angeles, Riverside and San Bernardino counties. This area of 10,000 square miles is home to nearly 16 million people. It is the second most populated urban area in the United States and one of the smoggiest.

AQMD is responsible for controlling emissions primarily from stationary sources of air pollution. These can include anything from large power plants and refineries to the local dry cleaner. Emission standards for mobile sources are established by the state or federal agencies, such as the California Air Resources Board (CARB) and the U.S. Environmental Protection Agency (EPA), rather than by local agencies such as the AQMD.

Under the Federal Clean Air Act, EPA establishes health-based ambient air quality standards that all states must achieve. The California Clean Air Act establishes additional standards to be met. AQMD develops plans to achieve these public health standards and adopts and implements regulations to reduce stationary source emissions in accordance with the plan.

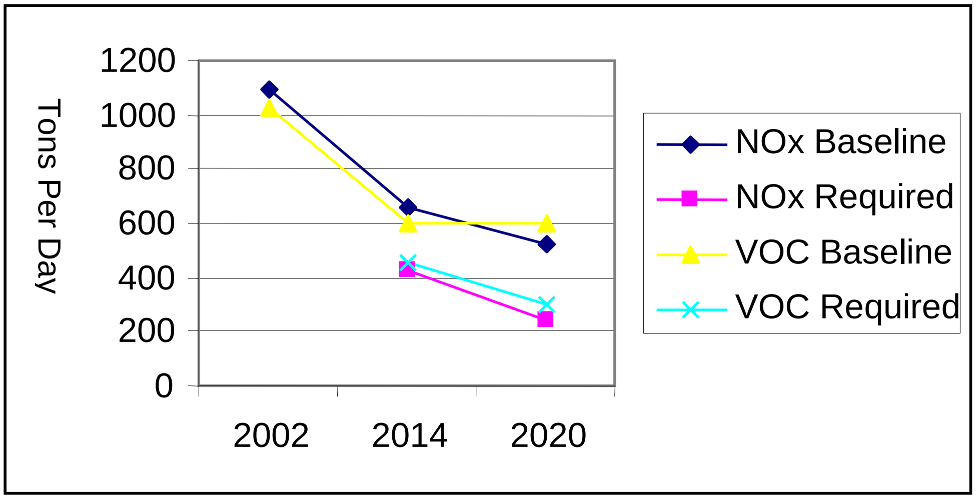
2007 DRAFT AQMP

Periodically the AQMD is required to prepare an Air Quality Management Plan (AQMP) achieve the ambient air quality standards. AQMD recently released the DRAFT 2007 AQMP, whose primary purpose is to achieve compliance with the new federal 8-hour ozone and fine particulate (PM2.5) ambient air quality standards. These new ambient air quality standards are more stringent than the previous 1-hour ozone standard and PM10 standards, and they require more emission reductions than the old standards. However the new standards do allow some additional time to comply: 2015 for the PM2.5 standards, and 2021 for the ozone standard.

Although the air quality in AQMD will continue to improve in future years, the existing local, state and federal regulations will not be adequate to achieve the new ambient air quality standards. Significant additional reductions of volatile organic compounds (VOC), oxides of nitrogen (NOx), oxides of sulfur (SOx) and PM2.5 are needed to attain of the federal air quality standards and protect public health. All four pollutants contribute to PM2.5 levels, directly or through reactions that form secondary PM2.5 in the atmosphere, while VOC and NOx are precursors to ozone formation.

Figure 1 shows the projected baseline emissions of NOx and VOC, based on current regulations, and the emission levels that need to be reached to achieve reach the PM2.5 standards in 2015 and the ozone standard in 2021. In order to meet the standards by those dates, the emission reductions must be achieved by 2014 and 2020. Although NOx and VOC will be significantly lower in 2014 and 2020 than current levels, they must be reduced another 50% and 54%, respectively, by 2020. In addition, SOx emissions must be reduced by 70% and direct PM2.5 emissions by 14% from baseline levels by 2014 to achieve the PM2.5 standards.

Figure 1 – NOx and VOC Baseline Emissions and Emission Needed to Achieve the PM2.5 and Ozone Standards



CURRENT RULE 1110.2

Rule 1110.2 was adopted in August 1990 to control NOx, carbon monoxide (CO), and VOC from gaseous and liquid-fueled internal combustion engines (ICEs). For all stationary and portable engines over 50 bhp, it required that either 1) NOx emissions be reduced over 90% to one of two compliance limits specified by the rule, or; 2) the engines be permanently removed from service or replaced with electric motors. It was amended in September 1990 to clarify rule language. It was then amended in August and December of 1994 to modify the CO monitoring requirements and to clarify rule language. The amendment of November 1997 eliminated the requirement for continuous monitoring of CO, reduced the source testing requirement from once every year to once every three years, and exempted nonroad engines, including portable engines, from most requirements. The last amendment in June 2005 made the previously exempt agricultural engines subject to the rule.

RECLAIM

In 1993 AQMD adopted Regulation XX – Regional Clean Air Incentives Market (RECLAIM). This regulation established NOx and SOx trading market emission reduction program that required over 300 of the largest sources in AQMD to meet the requirements of that program rather than the NOx requirements of other AQMD Rules. Therefore, some engines in AQMD are not subject to the NOx requirements of Rule 1110.2. They are still subject to the VOC and CO requirements of Rule 1110.2.

COMPLIANCE ISSUES WITH STATIONARY ENGINES

Current regulations require ICEs to demonstrate emission compliance only once every three years by an emission source test. This almost always results in a compliant source test because the operator will typically: schedule when the test will occur; service the engine and pre-test it to assure it is operating properly; test the engine at one load under steady-state conditions. Even if the test were to show non-compliance, only major sources (Title V) are required to report the results to AQMD.

Three years (up to 26,000 operating hours) is a long time between compliance checks. A lot can go wrong with an ICE during that three-year period. With an ICE used 24/7, it is typical to require an oil change once a month, and tune-ups every two months, including new spark plugs and oxygen sensors. A lot can go wrong to cause excess emissions including ignition system faults, a deteriorating catalyst, oxygen sensor failures, and simply falling out of adjustment.

AQMD Compliance Testing

In recent years, AQMD enforcement personnel acquired portable analyzers capable of measuring NOx, CO and O2 concentrations in the exhaust of combustion equipment. These analyzers are not expected to be as accurate as a Method 100.1 source test, but they are much easier and faster to set up and use, and can detect emission problems. A few AQMD inspectors have been using the portable analyzers to do unannounced emission tests on various types of combustion equipment.

These emission tests have shown that rich-burn ICEs, have very high non-compliance rates and very high excess emissions. As of December 30, 2005, 226 emission tests with portable analyzers have been conducted on ICEs driving electrical generators, compressors and pumps. The engines all were natural gas fired and rich-burn with 3-way catalytic emission controls. The equipment tested included engines manufactured by General Motors, Ford, Caterpillar, Jenbacher, Waukesha, Deutz and Daewoo, and packaged engine/cogeneration units manufactured by Tecogen, Hess and Coast Intelligen. The engines include a combination of older and new units. A majority of the engines tested were subject to Best Available Control Technology (BACT) limits of about 11 ppmvd[1] NOx and 70 ppmvd CO (corrected to 15% O2). The results of the tests are summarized in Tables 1, 2 and 3.

More than half of all engines tested were not in compliance with both their NOx and CO emission limits. Rich-burn engines had significantly higher non-compliance rates than the lean-burn engines.

The levels of non-compliance are extraordinary, as shown in Table 2. Extrapolating the results for the tested engines to the entire stationary, non-emergency engine inventory of nearly 1000 engines, results in estimated excess emissions of 5.1 tons/day of NOx and 65 tons/day of CO.

ICEs subject to BACT limits must comply with much lower concentration limits than non -BACT ICEs, but the statistics shown in Table 3 that the compliance rates of non-BACT ICEs are not much better than the BACT ICEs.

37 of the tests were retests of the same engine to verify that the violation had been corrected. But surprisingly, the compliance rate only improved from 44% of all first tests to 65% of all retests.

[1] Parts per million, by volume, dry

Table 1 – AQMD Compliance Test Statistics

	Rich-Burn Engines	Lean-Burn Engines
No. of Tests	215	11
No. of ICEs Tested	180	11
% of Tests on ICEs with BACT Limits	79%	91%
% Non-Compliance	51%	27%
% NOx Violations	40%	27%
% CO Violations	28%	0%

Table 2. AQMD Compliance Test Emissions

	NOx	CO
Rule 1110.2 Limits, ppm*	36-45	2000
Typical BACT Limits, ppm*	11	70
Maximum Test Concentration, ppm*	850	12,500
Average Violation Concentration, ppm*	137	2,520
Maximum % Over Limit	7,430%	18,400%
Average % Over Limit	912%	1,830%
Tested Excess Emissions, Tons/Year**	385	4,894
Estimated Total Inventory Excess Emissions, Tons/Year**	1,870	23,800

* All dry, by volume, and corrected to 15% O_2
** At 100% capacity factor

Table 3 – AQMD Compliance Test Statistics
BACT Versus Non-BACT ICEs

	BACT ICEs	Non-BACT ICEs
No. of Tests	179	47
% NOx Violations	39.1%	38.3%
% CO Violations	27.9%	23.4%

These poor compliance statistics make it clear that the periodic monitoring required by the existing rule is inadequate to assure compliance. When ICEs are properly maintained and operated they can achieve reasonably good emission levels. The 68 tests of BACT engines that were found in compliance averaged 4 ppm NOx and 30 ppm CO (@ 15% O2), well below BACT levels.

EPA REGULATIONS FOR STATIONARY ENGINES

New Source Performance Standards

Because of a Consent Decree, EPA began working on New Source Performance Standards (NSPS) for new stationary ICEs. They recently finalized regulations for compression-ignition (CI or diesel) engines and have proposed regulations for spark-ignition (SI) engines. The Consent Decree requires standards for SI engines to be promulgated by December of 2007.

<u>Compression-Ignition Engine New Source Performance Standards (CIE NSPS)</u>

On July 11, 2006, EPA issued final regulations to limit NOx, PM, CO and NMHC emissions from stationary CI engines, which are contained in Subpart IIII of 40 CFR 60. The CIE NSPS establishes requirements for manufacturers, owners, and operators of new (i.e. engines whose construction, modification or reconstruction began after July 11, 2005) stationary CI engines. The CIE NSPS requires the use of on-engine controls, after treatment and lower sulfur fuel to achieve the same emission standards as required for nonroad engines described in a later section. It also specifies monitoring, reporting, recordkeeping, and testing requirements. Except for CO, the emission standards are not as stringent as the limits in the current Rule 1110.2 until the Tier 4 emission standards go into effect from 2011 to 2015. Table F-2 in Appendix F provides a detailed summary of the key elements of CIE NSPS.

<u>Spark-Ignition Engine New Source Performance Standards (SIE NSPS)</u>

On June 12, 2006, EPA issued proposed New Source Performance Standards (NSPS) for stationary spark-ignition engines (SIE) that would apply to new (i.e. engines whose construction, modification or reconstruction began after a standard is proposed) stationary SIEs. The proposed new Subpart JJJJ of 40 CFR 60 will limit NOx, NMHC, and CO emissions. It also specifies monitoring, reporting, recordkeeping, and testing requirements.

The SIE NSPS requires the use of on-engine controls or after treatment to achieve the emission standards. For all SIEs < 25 hp, gasoline SIEs and rich-burn propane engines, the emission limits are those in the EPA regulations for nonroad SIEs (40 CFR Parts 90 and 1048).

Larger natural gas, digestor gas and landfill gas engines have proposed NOx limits that are less stringent the current Rule 1110.2. The proposed CO and NMHC limits for the same engines are more stringent than the current Rule 1110.2, but not as stringent as AQMD BACT for new engines. They start at 463 ppmvd CO and 203 ppmvd NMHC and drop to 232 ppmvd CO and 142 ppmvd NMHC by 2010/2011 for natural gas engines[2]. Landfill and digestor gas engines are limited to 579 ppmvd CO and 203 ppmvd NMHC.

National Emission Standards for Hazardous Air Pollutants (NESHAP)

On June 15, 2004, the EPA issued a final rule to reduce toxic air emissions (formaldehyde, acrolein, methanol, and acetaldehyde) from stationary engines, in the National Emission Standard for Hazardous Air Pollutants for Stationary Reciprocating Internal Combustion Engines (RICE NESHAP), Subpart ZZZZ of 40 CFR 63. The RICE NESHAP establishes requirements for large (> 500 horsepower) stationary engines, both CI and SI, located at major sources of hazardous air pollutants.

The RICE NESHAP requires installation of oxidation catalysts on lean-burn engines and three-way catalysts (also known as non-selective catalytic reduction (NSCR) catalysts) to reduce hazardous air pollutants and CO, and specifies recordkeeping, monitoring, and testing requirements. It requires that:

- Existing and new 4-stroke rich burn (4SRB) engines either reduce formaldehyde by 76 percent or limit the formaldehyde concentration to 350 parts per billion.
- New 2-stroke lean burn (2SLB) engines either reduce carbon monoxide (CO) by 58 percent or limit the formaldehyde concentration to 12 parts per million.
- New 4-stroke lean burn (4SLB) engines either reduce CO by 93 percent or limit the formaldehyde concentration to 14 parts per million.
- New compression ignition (CI) engines either reduce CO by 70 percent or limit the formaldehyde concentration to 580 parts per billion.

Formaldehyde and CO are surrogates for reducing the air toxics of concern from RICE. Therefore, by reducing formaldehyde and CO, facilities also will reduce the other organic air toxics.

Only two facilities have notified EPA that they are subject to the major source RICE NESHAP: the natural gas storage facilities in Northridge and Santa Clarita operated by Southern California Gas Company.

Additional information about this regulation is found in Appendix F.

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[2] Corrected to 15% O2 and assuming an engine efficiency of 30% based on higher heating value of the fuel.

On June 12, 2006, EPA proposed amendments to Subpart ZZZZ that will apply to new or reconstructed RICEs under 500 hp at major sources, and new or reconstructed RICEs at minor sources. In general these RICEs will only have to comply with the proposed RICE SI NSPS or the adopted RICE CI NSPS. The exception is that new SI 4SLB RICEs from 250 to 500 hp (not including digestor or landfill gas fired RICEs) will have to reduce CO by 93% or limit the formaldehyde concentration to 14 ppmvd.

Nonroad Engines

EPA regulates new nonroad engines. Nonroad engines include: engines that propel off-road equipment such as trains and bulldozers, and; portable engines that drive generators and wood chippers and other equipment, and that are moved from place to place. Nonroad engines include CI and SI engines using diesel fuel, propane, gasoline and other fuels.

The Nonroad Preemption

The Clean Air Act Amendments of 1990 limit the ability of states and local districts to regulate nonroad engines. Only EPA can set emission standards for new construction and farm equipment under 175 hp. Federal regulations[3] allow California to regulate all other nonroad engines with an authorization from EPA. States and local districts can also regulate the use of nonroad engines.

Nonroad Diesel Engine Regulations

EPA has been regulating new nonroad diesels since 1996 in 40 CFR 89 Subpart A, Appendix A and 40 CFR 85 Subpart Q. Tier 1, Tier 2 and Tier 3 standards are in effect or are partly in effect, and recently adopted and stringent Tier 4 standards will go into effect in the next decade. The emission standards vary by engine size, but as an example Table 4 shows the standards for nonroad diesel engines from $100 \leq hp < 175$.

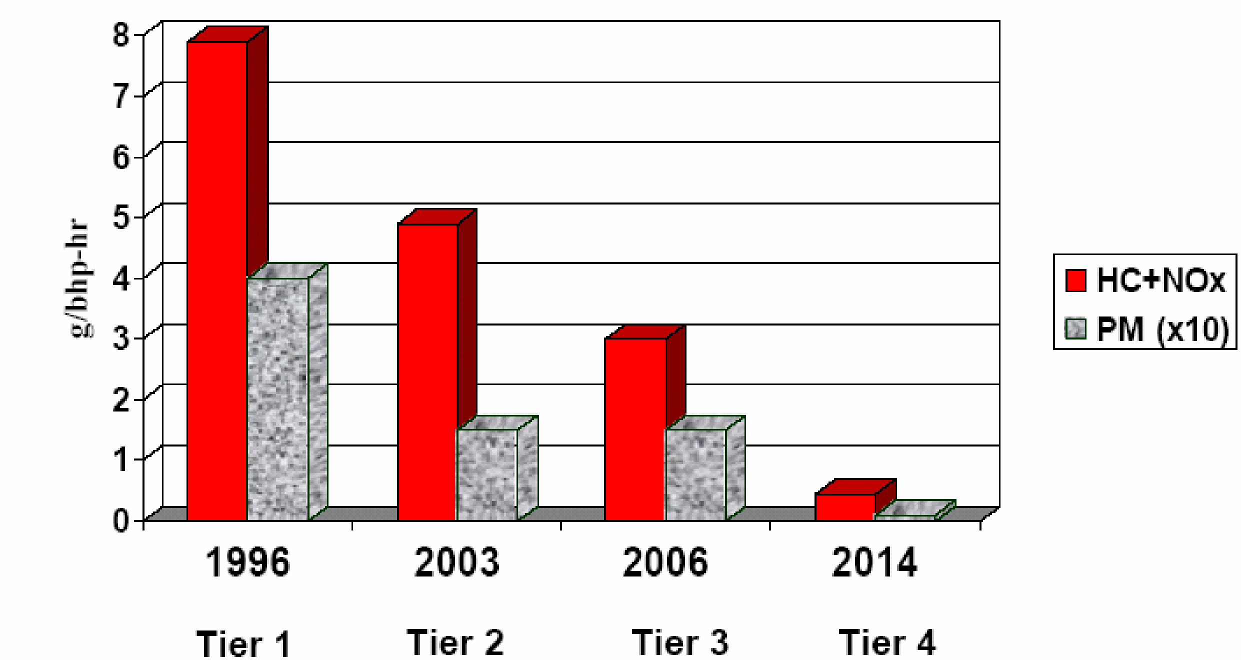
Table 4. EPA Nonroad Diesel Engine Emission Standards
175 ≤ hp < 300 (grams/bhp-hr)

	Implementation Date	CO	NMHC	NOx + NMHC	NOx	PM
Tier 1	1996	8.5	1.0	-	6.9	-
Tier 2	2003	2.6	-	4.9	-	0.15
Tier 3	2006	2.6	-	3.0	-	0.15
Tier 4	2012-2014	2.6	0.14	-	0.30	0.015

[3] 40 CFR 89, Subpart A, Appendix A and 40 CFR 85, Subpart Q

Figure 2 demonstrates the remarkable emission reductions that the Tier 4 emission limits will achieve. These limits are more stringent than Rule 1110.2.

Figure 2. EPA Nonroad Diesel Emission Standards for a 175 hp Engine



Nonroad Spark-Ignited (SI) Engine Regulations

EPA has been regulating new nonroad SI engines over 25 Hp since 2004 in 40 CFR 1048. Most of these engines use liquefied petroleum gas (propane), with others operating on gasoline or natural gas. EPA adopted two tiers of emission standards shown in Table 3. The first tier of standards, which started in 2004, are based on a simple laboratory measurement using steady-state procedures. The Tier 1 standards are the same as those adopted earlier by CARB for engines used in California. The Tier 2 standards, starting in 2007, are based on transient testing in the laboratory, which ensures that the engines will control emissions when they operate under changing speeds and loads in the different kinds of equipment. EPA includes an option for manufacturers to certify their engines to a less stringent CO standard if they certify an engine with lower HC+NOx emissions. In addition to these exhaust-emission controls, manufacturers must take steps starting in 2007 to reduce evaporative emissions, such as using pressurized fuel tanks.

Table 3. EPA SI Engine Emission Standards (grams/bhp-hr)

	Implementation Date	HC + NOx	CO
Tier 1	2004	3.0	37
Tier 2	2007	2.0	4.4

Starting with Tier 2, EPA adopted additional requirements to ensure that engines control emissions during all kinds of normal operation in the field. Tier 2 engines must have engine diagnostic capabilities that alert the operator to malfunctions in the engine's emission-control system.

CARB REGULATIONS AND GUIDANCE

CARB Guidance for Stationary Spark-Ignited Engines

In 2001, CARB published "Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Spark-Ignited Internal Combustion Engines" as guidance for local air districts in adopting rules for stationary spark-ignited engines. Because of compliance problems with engines, it recommended more frequent source testing than Rule 1110.2, and an Inspection and Monitoring Plan requiring periodic monitoring and maintenance, including the use of a portable emission analyzer.

Air Toxic Control Measures for Diesel Engines

CARB has adopted Air Toxic Control Measures (ATCMs) for both stationary and portable diesel engines. The purpose of these ATCMs is primarily to reduce diesel PM, but they will result in reductions of the other pollutants as well.

<u>Stationary Diesel ATCM</u>
AQMD has adopted its version of the stationary diesel ATCM in the form of Rule 1470. It requires emergency diesel engines to: limit the annual operating hours for maintenance and testing; avoid operation during school hours when near a school: and install a diesel particulate filter when located within 328 feet of a school. Non-emergency diesel engines, with some notable exceptions, must also install a diesel particulate filter.

Existing stationary agricultural engines were not subject to the original stationary diesel ATCM, but on November 16, 2006, CARB adopted amendments to the ATCM that make them subject to the rule. The ATCM requires the following for stationary agricultural diesel engines, not including wind machines, emergency engines, or engines <50 hp:

- Except for generator sets, uncertified engines from 51 to 750 hp must meet Tier 3 diesel emission requirements by December 31, 2010 or December 31, 2011, depending on horsepower. This will cause operators of engines eligible for the January 1, 2014 compliance date allowed by paragraph (h)(12) of Rule 1110.2 to have to act sooner to comply with the ATCM and Rule 1110.2

- Generator sets, uncertified engines over 750 hp, and Tier 1 or Tier 2 engines must meet Tier 4 diesel emission requirements by December 31, 2014 or December 31, 2015, depending on horsepower. By these dates these same engines will already be required to be in compliance with Rule 1110.2.

- Operators must register their engines with local air pollution control districts by submitting detailed information about each engine. The regulation also allows local districts to charge fees for this registration.

Portable Diesel ATCM

CARB adopted a portable diesel ATCM (Sections 93116 through 93116.5 of Title 17 of the California Code of Regulations) on February 24, 2004, which will have a significant effect on portable diesel engines > 50 hp. Its requirements include:

- As of January 1, 2006 any newly permitted portable diesels must be certified to the current model year standards (Tier 2 or Tier 3 depending on the horsepower). However, CARB recently adopted emergency rules to loosen this requirement to allow resident Tier 1 and 2 engines to continue to operate.
- By January 1, 2010, uncertified portable diesels may no longer be used in California.
- Operators of portable diesel fleets must reduce the fleet average PM emissions to lower and lower levels by 2013, 2017 and 2020 by engine replacements or retrofit of PM control devices.

Agricultural portable engines are subject to this ATCM.

CARB Portable Equipment Registration Program (PERP) Regulation

Health & Safety Code Sections 41750-41755 (Assembly Bill 531), effective January 1, 1996, required CARB to adopt regulations to establish a statewide registration program for portable engines and other equipment. CARB adopted the regulation on March 27, 1997. Portable engine owners or operators may register under the statewide program or get a permit from AQMD. Those that register with CARB are exempt from AQMD permits and emission requirements. As of January 1, 2006, newly registered engines must be certified to the current model year standards (Tier 2 or Tier 3 depending on the horsepower). However, CARB adopted emergency rules to to loosen this requirement to allow resident Tier 1 and 2 engines to continue to be registered. Portable agricultural engines are not eligible for the CARB PERP program.

Off-Road Diesel Engines

CARB began regulating new off-road[4] diesel engines before EPA, but later harmonized its regulations in Title 13, Chapter 9, Article 4 of the California Code of Regulations (CCR) with EPA nonroad diesel emission standards. On December 9, 2004 CARB approved amendments to incorporate EPA Tier 4 standards into state law, although the regulation is not final until approved by the Office of Administrative Law. The emission standards will be the same as EPA's, but there are some minor differences in other areas.

Off-Road Spark-Ignited (SI) Engines

CARB has been regulating new off-road SI engines over 25 hp since 2001 in Title 13, CCR, Chapter 9, Article 4.5. The emission standards are shown in Table 4.

Table 4. CARB Off-Road SI Engine Emission Standards (grams/bhp-hr)

Implementation Date	Engine Displacement	HC + Nox	CO
2002	≤ 1.0 Liters	9.0	410
2001-2003	> 1.0 Liters	3.0	37

[4] EPA uses the term nonroad for the same purpose.

These standards are less stringent than EPA standards that went into effect in 2004 (see earlier discussion.) However, CARB staff is working on, and has begun workshops for, new regulations to reduce emissions from both new and in-use off-road SI engines.

EPA DISAPPROVAL OF RULE 1110.2

EPA proposed the disapproval of Rule 1110.2 and recommended the following changes (Reference 10) to enable approval of the rule:

- An inspection and monitoring plan similar to CARB' RACT/BARCT document
- Source testing every two years or 8,760 hours
- Source testing at peak load as well as at under typical duty cycles
- A removal of the exemptions for engines at ski resorts, the far eastern portion of Riverside County, and San Clemente Island

ELECTRICAL GENERATION TECHOLOGIES

California Electricity Supplies

As California's population and energy demands increase, there is certainly a need for increased electric generation equipment in California. CEC estimates that between 2003 and 2013, approximately 10,000 MW (including reserves) of generation or demand-reducing programs will be needed to serve the growth in the state economy.[5] The increased power demand can be met by large central generating stations, by distributed generation (DG) or a combination of the two.

From 2001 to 2003, over 7,200 MWs of electrical generating capacity were added in California[6], but only 376 MWs of DG were added in the service territories of the three large investor-owned utilities in California[7]. The vast majority of the additions were from large central generating stations. Although the DG is not a large part of the overall growth in electrical generating capacity, its air quality impacts per MW can be much higher than for large central generating stations.

Figure 3 shows the sources of electricity in California in 2003. Because of the large quantities of hydroelectric, nuclear, wind, solar and imported power, 59% had zero emissions in California.

Figure 4 demonstrates the remarkable reductions in emissions from central generating stations in AQMD. Since 1969, NOx and SOx emissions have been reduced about 99%. This has been achieved by replacing many power plants with new, more efficient and cleaner combined-cycle gas turbines, installing selective catalytic NOx controls on the remaining older power plant, and using natural gas.

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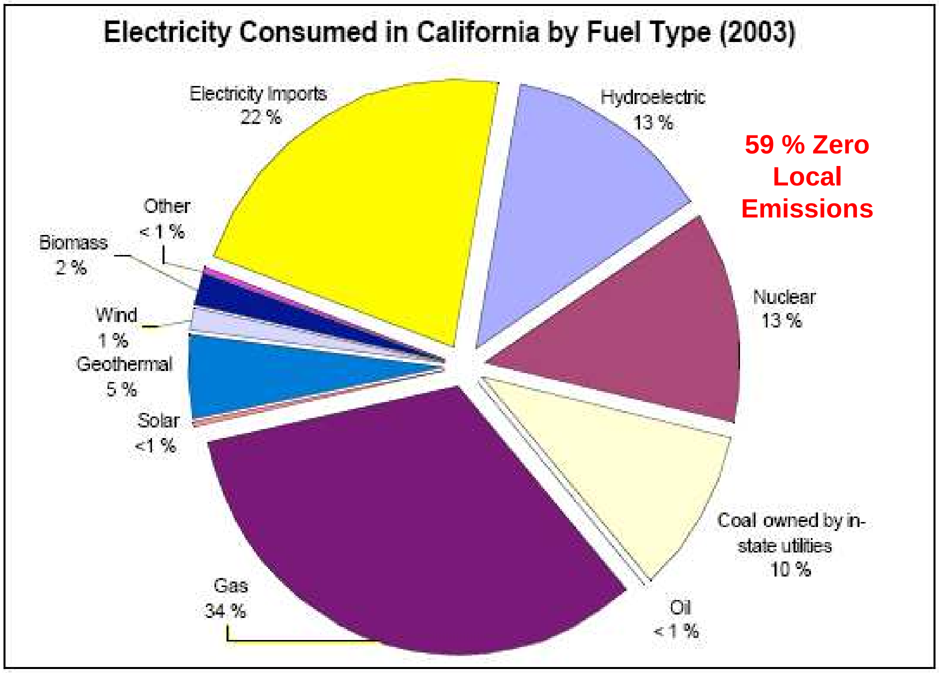
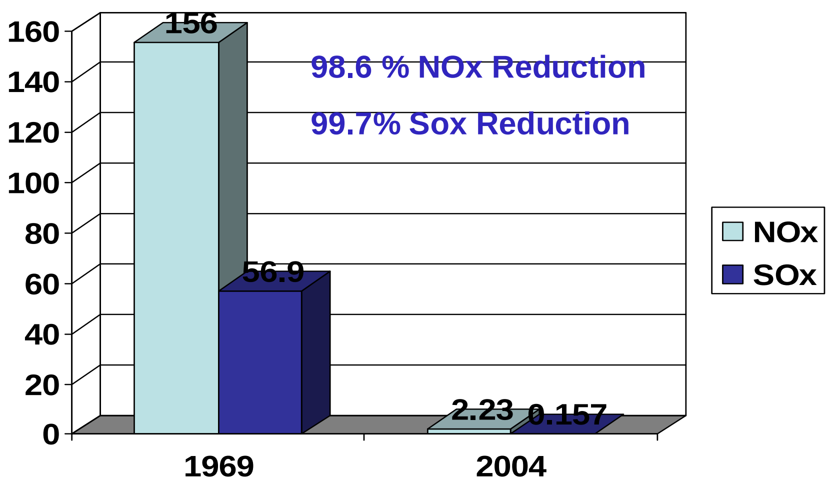
[5] Electricity and Natural Gas Report, California Energy Commission, December 2003
[6] IBID
[7] http://www.energy.ca.gov/distgen/interconnection/rule21_stats.html

Figure 3



Source: California Energy Commission's 2004 QFER data, Table J-11

Figure 4. SCAQMD Central Generating Station Emissions, Tons/Day



CARB Distributed Generation Guidelines

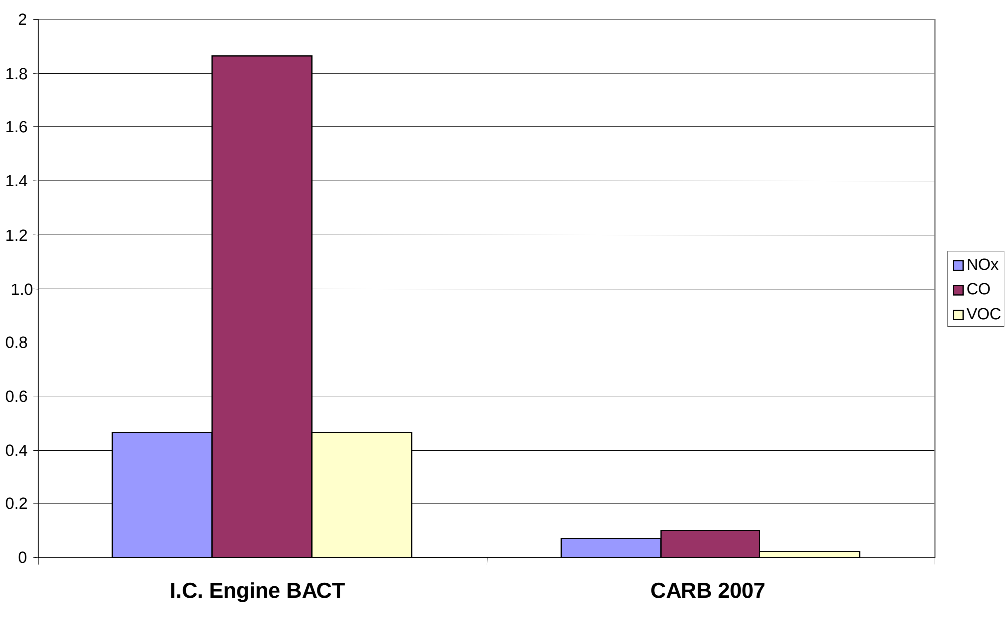
Senate Bill 1298[8] was adopted in 2000 by the California state legislature to close a loophole for small electric generators that were exempt from local district permits and not required to have emission controls. In accordance with the law, CARB adopted the Distributed Generation Certification Program[9] for small generators that are exempt from local district permitting requirements. In AQMD, this includes ICE generators of 50 hp or less, microturbines, and fuel cells. As of January 1, 2007 these electrical generation technologies may only be sold in California if they are certified by CARB to have emissions equivalent or better than large central generating stations equipped with BACT.

SB 1298 also established a goal to have local districts require permitted distributed generation (DG) equipment to meet the same emissions levels by the earliest practicable date.

Comparison of Emissions from Central Power Plants and ICE Distributed Generation

The current BACT requirements for ICE distributed generation (DG) permitted by AQMD allow emissions that are from 6 to 23 times higher than the emissions allowed from new large central station power plants. Figure 5 demonstrates the differences between the BACT emission limits for an ICE and the CARB 2007 DG standards, which are equivalent to the BACT emission limits for a new large central station power plant.

Figure 5. Current BACT for DG (I.C. Engine versus CARB's 2007 DG Standards



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8 Sections 41514.9 and 41514.10 of the California State Health and Safety Code

9 Sections 94200-94214, in Article 3, Subchapter 8, Chapter 1, Division 3 of Title 17, California Code of Regulations

Characteristics of Central Power Plants

As shown in the previous Figure 4, AQMD regulations have been incredibly successful in reducing NOx and SOx emissions from central power plants. The reductions have occurred as a result of using natural gas instead of fuel oil, repowering some plants with modern, efficient, and combined cycle gas turbines with BACT emission controls, and retrofitting the older power plants with selective catalytic reduction NOx controls.

New central station power plants also:

- Are installed only when additional electric power is needed;
- Are only operated when needed, often as peaking units
- Provide emission offsets for all emission increases to mitigate emission impacts;
- Have continuous emission monitoring systems (CEMS) for NOx and CO;
- Must promptly report emissions exceedances to AQMD; and
- Are staffed 24/7 by personnel who can respond to and correct emission problems;

Characteristics of Distributed Generation

All DG produce the same product, electricity. Some DG also produces useful thermal energy.

Air emissions from DG vary widely. Solar photovoltaic and wind power DG produce zero emissions. Fuel cells have near zero emissions and can meet the CARB 2007 DG emission standards. Large gas turbine cogeneration DG (over 3MW) are very similar to large central power plants, have the same emission controls and comparable emissions. But, the majority of DG projects are comprised of ICE DG which, as shown in Figure 5, are permitted to have much higher emissions than large central power plants or clean DG.

In comparison to large central power plants, ICE DG are:

- Discretionary. Facilities install ICE DG in anticipation of economic benefits, not because there is a need for power. Facilities can also use clean grid power.
- Are often used as a 24/7 baseload unit, whether the electric grid needs the power or not.
- Usually exempt from providing emission offsets because their permitted emissions are below the New Source Review offset thresholds.
- In most cases not required to have CEMS[10]
- Generally not required to report emission exceedances to AQMD[11]
- Are often operated without onsite supervision or trained operating personnel

DG Technologies that Meet CARB 2007 DG Standards

CARB has certified that the following DG equipment meet the 2007 standards.

[10] Only engines over 1000 HP are currently required to have CEMS for NOx. None are required to have CO CEMS.
[11] Only Title V major sources are required to report emission exceedances.

Table 5 – Certified Technologies to CARB 2007 DG Standards

Company Name	Technology
United Technologies Corporation Fuel Cells	200 kW, Phosphoric Acid Fuel Cell
FuelCell Energy, Inc.	250 kW, DFC300A Fuel Cell
Plug Power Inc.	5 kW, GenSys™ 5C Fuel Cell
FuelCell Energy, Inc.	1 MW, DFC1500 Fuel Cell
Ingersoll-Rand Energy Systems	250 kW, 250SM Microturbine
FuelCell Energy, Inc.	250 kW, DFC300MA Fuel Cell
ReliOn, Inc.	2 kW, T-2000 hydrogen-fueled fuel cell
ReliOn, Inc.	1.2 kW, T-1000 hydrogen-fueled fuel cell

The following DG technologies don't require CARB certification, because they normally get AQMD permits, but they can also meet CARB's 2007 emission standards:

- Kawasaki GPB15X Gas Turbine--1.423 gross MW at ISO conditions (sea level, 59^{o}F), guaranteed emission limits of 2.5 ppm NOx, 6 ppm CO and 2 ppm VOC, all dry basis, corrected to 15% O2, down to 70% of rated load. These emission limits together with heat input of 20.7 MMBtu/hr (LHV) and 53.7% waste heat recovery specified by the manufacturer meet the CARB 2007 standards.
- Large combustion gas turbines with combined heat and power (CHP). These are very similar to the central station combined-cycle power plants that are the basis of the 2007 CARB DG standards.

In addition, facilities may install other DG technologies such as: zero-emission solar or wind DG. All of the above technologies are either inherently low-emission, or will have CEMS to assure proper operation of their add-on emission controls.

State of California Initiatives for Clean DG

The State of California recognizes the need for clean electric power and led the way in requiring clean and renewable electric power. Recent legislation includes the following bills.

SB1298: This required CARB to establish the 2007 DG standards for small unpermitted DG units and to issue guidance to local air districts by the earliest practicable date to require DG BACT for permitted DG units that is equivalent to BACT for central station power plants.

AB1685: This limits the self generation incentives provided by the local utilities to DG projects that meet the CARB 2007 DG standards beginning January 1, 2007. It also provides the highest incentives to solar, fuel cell and renewable DG.

SB1078: This requires the investor-owned utilities to increase electric generation from renewable technologies to 20% of total generation by 2010. This will spur more solar, wind and other renewable projects and make the grid electric power even cleaner than it is today.

SB1652/SB1: The Million Solar Roofs plan has a goal to install 3,000 MW of solar photovoltaic systems on new houses in California by 2018.

Staff's proposal to require new DG to be as clean as new grid power is in line with the State's initiatives.

ICE Advancements

Advancements are being made in ICE technologies that may lead to them being able to also achieve the CARB 2007 DG standards. The California Energy Commission's Advanced Reciprocating Internal Combustion Engine Collaborative provides funding to ICE project with the goal of achieving the CARB 2007 DG standards by increasing the efficiency and reducing the emissions from ICEs. The projects involve cooled exhaust gas recirculation with a three-way catalyst, homogeneous charge compression ignition, and advanced laser ignition.

CHAPTER 2: AFFECTED SOURCES & EMISSION INVENTORY

AFFECTED SOURCES

PAR 1110.2 applies to stationary and portable reciprocating ICEs over 50 brake horsepower (bhp). ICEs generate power by combustion of an air/fuel mixture. In the case of spark-ignited (SI) engines, a spark plug ignites the air/fuel mixture while a diesel engine relies on heating of the inducted air during the compression stroke to ignite the injected diesel fuel. Most stationary and portable ICEs are used to power pumps, compressors, or electrical generators.

SI engines come in a wide variety of designs such as: two-stroke and four-stroke, rich-burn and lean-burn, turbocharged and naturally-aspirated. SI engines can use one or more fuels, such as natural gas, oil field gas, digester gas, landfill gas, propane, butane, liquefied petroleum gas (LPG), gasoline, methanol and ethanol. ICEs can be used in a wide variety of operating modes such as: emergency operation (i.e. used only during testing, maintenance, and emergencies), seasonal operation, continuous operation, continuous power output, and cyclical power output. Additional information about SI engines is found in Appendix D.

The diesel engine is another type of ICE: specifically, a compression ignition (CI) engine, in which the diesel fuel is ignited solely by the high temperature created by compression of the air-fuel mixture, rather than by a separate source of ignition, such as a spark plug, as is the case with SI engines. Similarly to SI engines, there are both two-stroke and four-stroke diesel engines. Most diesel engines are four-stroke, with larger diesels often two-stroke, mainly the huge engines in ships and locomotives.

Diesel engines are most commonly used for portable equipment and emergency stationary generators, fire pumps and water pumps. Stationary diesel engines are also used for more routine use at a few locations that have been exempted from complying with Rule 1110.2. These include engines operated by the US Navy on San Clemente Island, and engines at ski resorts. Some diesel engines at RECLAIM facilities also continue to operate because they were exempted from the NOx emission requirements of Rule 1110.2.

Uncontrolled ICEs, even when burning a clean fuel such as natural gas, have extremely high emissions of NOx, CO and HC. Diesel engines not only have significant NOx emissions but also emit particulate matter (PM) which has been identified as a Toxic Air Contaminant (TAC) by the CARB. Once a substance is identified as a TAC, the CARB is required by law to determine if there is a need for further control. CARB has adopted Airborne Toxic Control Measures (ATCM) for stationary and portable diesel engines.

EMISSIONS INVENTORY

Portable Engines

CARB estimates that in 2000 17,500 portable diesel engines in California emitted 67.1 tons/day of NOx, 6.7 tons/day of ROG and 4.2 tons/day of PM. Emissions in SCAQMD would be about 45% of this amount. These emissions should gradually decline as newer CARB-certified portable engines replace older, higher emitting engines.

Stationary Non-Agricultural Engines

The 1990 staff report for proposed Rule 1110.2 estimated that Rule 1110.2 would reduce NOx emissions of 1,289 stationary, non-emergency engines from 28.0 tons/day to 2.9 tons/day. Exemptions in 1997 for ski resorts and San Clemente Island increased the allowable emissions by 1.35 tons/day to an estimated 4.25 tons/day.

Stationary Engine Survey

To update this information as well as gather other key information for non-agricultural engines that are affected by the rule, staff conducted a survey in 2005 of non-agricultural, stationary, non-emergency engines. A total of 580 facilities were contacted, and 313 of those facilities responded (54% facility response rate). The survey collected data for 631 out of a total of 907 active engines (70% response rate based on number of engines). The results of the survey are presented in Appendix A.

Emissions were calculated based on fuel consumption data gathered via the survey, but because source test emission data often underestimate real emissions, emission concentration limits were used for some of the engines to make the estimates more realistic. The resulting calculated total emissions for all survey engines were scaled up to account for the 70% response rate. The resulting total calculated emissions for all stationary, non-emergency engines in the district, in tons/day, are 3.29 NOx, 1.47 VOC and 11.2 CO. The calculated current NOx emissions indicate that substantial progress has been made since 1990, and the calculated NOx emissions are probably less than the 4.25 tpd level that was expected.

As mentioned earlier in the report, a program of unannounced compliance testing conducted by AQMD's Compliance department revealed that, although engines can generally meet emission limits when emission control systems are properly maintained and adjusted as is generally the case at the time of source testing, emissions during normal operation frequently exceed the emission limits. The tendency for an engine to have excess emissions will differ depending upon whether it is a rich-burn or lean-burn engine, what emission limits it must meet (BACT or Rule 1110.2) and whether or not it has a CEMS. Table 6 shows the average ratio of measured emissions to allowed emissions found in the testing program with engines categorized based on these three parameters.

Table 6. Average Ratio of Measured Emission to Allowed Emission Found in Unannounced Testing

Rich/Lean	Limits	CEMS	Tests	NOx	CO
Lean	BACT	No	3	1.81	0.33
Lean	BACT	Yes	7	0.76	0.39
Lean	Rule	No	1	0.89	0.10
Rich	BACT	No	169	5.19	5.21
Rich	BACT	Yes	8	0.11	37.76
Rich	Rule	No	39	2.12	0.70

Excess emissions of both NOx and CO were clearly evident from rich-burn engines with BACT limits not having CEMS. Excess emissions of CO were evident from rich-burn engines with BACT limits having CEMS and of NOx from rich-burn engines with Rule 1110.2 limits not having CEMS. Although there was some suggestion of excess NOx emissions from lean-burn engines with BACT limits not having CEMS, the number of tests was considered too small to be conclusive, and lean-burn engines are less likely to have large exceedances. There were no tests on rich-burn engines with Rule 1110.2 limits having CEMS.

To estimate the extent of excess emissions from the engine population in the district, staff applied factors of 4 to the calculated NOx, CO and VOC emissions from rich-burn engines with BACT limits and not having CEMS, a factor of 37 to calculated CO and VOC emissions from rich-burn engines with BACT limits having CEMS and a factor of 1 to calculated NOx emissions from rich-burn engines with Rule 1110.2 limits not having CEMS. Applying the CO factor also to VOC was justified based on the general observation that these pollutants generally trend together. Again, scaling the results based on the 70% survey response rate, the estimated excess emissions in tons per day are 1.29 NOx, 5.40 VOC and 21.7 CO.

Table 7 summarizes the calculated emissions based on the survey data, the estimated excess emissions based on the average exceedance factors found in compliance testing and the resulting total calculated/estimated emissions from stationary, non-emergency engines.

Table 7. Emissions from Stationary, Non-Emergency Engines (TPD)

	NOx	**VOC**	**CO**
Calculated Based on Limits and Source Tests	3.29	1.47	11.2
Estimated Excess Emissions	1.29	5.40	21.7
Totals	4.58	6.87	32.9

Largest Stationary Engine Emissions Facilities

Using data reported annually to AQMD, staff identified the “top 25” facilities in terms of NOx emissions from stationary, non-emergency engines. Data sources consisted of the 2005-2006 Annual Emissions Report (AER) and the RECLAIM Annual Permit Emissions Program (APEP) report for 2005-2006 or 2005, depending on the RECLAIM cycle. The “top 25” facilities are listed in Table 8 along with the annual pounds-per-year (ppy) emissions of NOx, CO, and ROG, SOx.

The data are all self-reported by the facilities. Except for the data based on CEMS, the emissions are probably on the low side.

The diesel engines on San Clemente Island (US Navy) and Catalina Island (Southern California Edison Co.) are the two largest NOx emitters with about 34% of the total emissions. Joined with four other facilities with diesel engines on the list, they comprise 24% of the 25 facilities. All of these facilities are in RECLAIM and not subject to Rule 1110.2, or otherwise exempt from Rule 1110.2.

Biogas engines are prominent on the list with the two Orange County Sanitation Districts facilities taking up numbers 3 and 4 on the list for NOx, and higher positions for VOC and CO. Ten of the top 25 (40%) burn biogas, and are subject to Rule 1110.2 because they were exempted from RECLAIM.

Table 8. "Top 25" Facilities with Highest NOx Emissions from Stationary, Non-Emergency Engines (Pounds per Year)

Facility	ID No.	NOx	ROG	CO	Fuel(s)
U.S. GOVT, DEPT OF NAVY	800263	235,124	23,437	63,749	Diesel
SO. CAL. EDISON CO.	4477	213,022	94,689	257,553	Diesel
SANITATION DISTRICTS OF ORANGE CO.	29110	118,862	56,434	589,640	Digester & Natural Gas
SANITATION DISTRICTS OF ORANGE CO.	17301	112,712	59,245	231,454	Digester & Natural Gas
AERA ENERGY LLC	104012	78,040	1,542	5,367	Diesel
SO. CAL. GAS CO.	5973	69,144	41,315	179,278	Natural Gas (Lean-Burn & Rich-Burn)
SAN DIEGO GAS & ELECTRIC	4242	59,625	16,490	44,814	Natural Gas (Lean-Burn)
PENROSE LANDFILL GAS CONVERSION, LLC	142408	55,661	21,356	246,617	Landfill Gas
RIDGEWOOD POWER MANAGEMENT,LLC	113518	54,798	1,261	9,558	Landfill Gas
SNOW SUMMIT INC	43201	52,350	7,391	39,420	Diesel
CHINO BASIN DESALTER AUTHORITY	135216	43,813	3,024	43,165	Digester Gas
SO. CAL. GAS CO.	800128	36,833	30,662	112,268	Natural Gas (Lean-Burn & Rich-Burn)
TOYON LANDFILL GAS CONVERSION, LLC	142417	29,305	3,568	107,379	Landfill Gas
SO. CAL. GAS CO./PLAYA DEL REY STORAGE FACILITY	8582	25,515	3,498	11,482	Natural Gas (Lean-Burn & Rich-Burn)
INLAND EMPIRE UTILITIES AGENCY	9163	23,064	9,236	148,283	Digester Gas
TIDELANDS OIL PRODUCTION CO.	68118	21,792	21,792	87,169	Field Gas
DISNEYLAND RESORT	800189	19,204	3,334	202,409	Natural Gas (Rich-Burn)
RIVERSIDE CITY, WATER QUALITY CONTROL	9961	14,865	3,365	68,389	Landfill & Digester Gas
GARRETT ENGINE BOOSTING SYSTEMS	68996	14,313	3,602	9,798	Diesel
EASTERN MUNICIPAL WATER DISTRICT	70296	11,839	7,892	19,730	Natural Gas (Rich-Burn)
SO. ORANGE CO. WASTEWATER AUTHORITY	13433	10,684	8,874	54,917	Natural & Digester Gas
POMONA VALLEY COMMUNITY HOSP.	800212	9,482	6,857	10,531	Natural Gas (Rich-Burn)
CONOCOPHILLIPS CO.	800363	7,787	54	4,184	Diesel
EASTERN MUNICIPAL WATER DISTRICT	1703	7,517	3,847	24,140	Natural & Digester Gas
VINTAGE PETROLEUM INC	101369	7,276	2	2,459	Field Gas (Rich-Burn)
TOTALS, LB/YR		1,332,627	432,767	2,573,753	
TOTALS, TPD		1.83	0.59	3.53	

The three SoCalGas storage facilities and one SDG&E compressor station, all in RECLAIM, are the highest emitting natural gas-fired facilities. Nine of the top 25 (36%) facilities burn natural gas or field gas.

CHAPTER 3: CONTROL TECHNOLOGIES

INTRODUCTION

Without any emission controls, ICEs have the highest emissions of all combustion equipment in terms of emissions per unit of fuel use. Fortunately, there are emission controls for ICEs. They include combustion modifications and add-on control technologies. The types of controls that are used depend on the fuel used and whether the ICE is rich-burn or lean-burn.

SPARK-IGNITION (SI) ENGINE EMISSIONS AND EMISSION CONTROL TECHNOLOGIES

SI Engines and Uncontrolled Emissions

SI engines fall into two major design categories. Four-stroke, rich-burn engines are designed to operate close to stoichiometric conditions. In other words, they draw just the necessary amount of air to combust the fuel and little, if any, more. These engines operate with exhaust gas oxygen content very near zero. The other category is lean-burn engines, which are designed to draw substantially more air than is required for combustion and operate with a high level of exhaust gas oxygen, typically over 5%. Larger engines tend to be lean-burn, and smaller engines tend to be rich-burn. Typical emissions of NOx, CO and VOC from uncontrolled natural gas-fired engines are listed in Table 9. The emission factors in the table are from U.S. EPA's AP-42[12] Emissions produced by engines operating on fuels other than natural gas may differ from those listed in Table 9, but should be similar. NOx emissions from engines operating on landfill or digester gas should be significantly lower due to the thermal diluent effect of CO2 present in these types of waste gas.

Table 9. Uncontrolled Emissions from Natural Gas-Fired SI Engines *

	Rich-Burn	**Lean-Burn**
	$Lbs/MMBtu_{HHV}$	**$Lbs/MMBtu_{HHV}$**
NOx	2.21	4.08
CO	3.72	0.317
VOC	0.0296	0.118
	ppmvd @ 15% O_2	**ppmvd @ 15% O_2**
NOx	590	1090
CO	1629	139
VOC	23	91

*g/Bhp-hr = lb/MMBtu x 1.15 / ($\%EFF_{HHV}$/100)

ppmvd@15%O2 = lb/MMBtu x F (F = 267 for NOx, 438 for CO, 767 for VOC as methane)

[12] U.S. EPA AP-42 Compilation of Air Pollution Emission Factors, Tables 3.2-2 and 3.2-3.

CARB RACT/BARCT Determination

In November 2001, CARB published a RACT/BARCT determination (Reference 1) for stationary SI engines. This determination, while not aggressive for CO or VOC, identified a number of NOx control technologies that are effective for stationary SI engines (Table 10) and recommended significant reductions in NOx (Table 11). Lean-burn SI engines that are subject only to Rule 1110.2, and not to BACT, will generally be equipped with low-emission combustion improvements, whereas rich-burn SI engines will have a three-way catalyst (TWC), also known as non-selective catalytic reduction (NSCR), which along with accurate control of the air/fuel ratio to near stoichiometric conditions, simultaneously reduces the three pollutants NOx, CO and VOC.

Table 10. NOx Control Technologies for Stationary SI Engines

Technology	NOx Reduction Capability, %	Comments
Ignition Timing Retard	15-30	Reduces efficiency by up to 5%
Pre-Stratified Charge (PSC)	80+	Not suitable for lean-burn engines
Low-Emission Combustion Modifications	80+	Pre-combustion chamber, leaning, ignition system improvement, turbocharger, air/fuel ratio control system. Retrofit kits are available for some engines.
Turbocharger with Aftercooler	3-35	
Exhaust Gas Recirculation (EGR)	30	
Non-selective Catalytic Reduction (NSCR)	90+	Three-way catalyst—reduces NOx, CO and VOC. Not suitable for lean-burn engines.
Selective Catalytic Reduction (SCR)	80+	Requires injection of urea or ammonia to react with NOx. Unreacted ammonia is emitted. Oxidation catalyst is normally included to reduce CO and VOC emissions.

Table 11. CARB NOx RACT/BARCT Determination for Stationary SI Engines (ppmvd corrected to 15% O2)

	Rich-Burn	Lean-Burn
RACT	90% control or 50 ppm NSCR, PSC for waste gases	80% control or 125 ppm Low-Emission Combustion or SCR
BARCT	96% control or 25 ppm NSCR, Inspection & Maintenance Program Waste Gases: 90% control or 50 ppm PSC	90% control or 65 ppm Low-Emission Combustion Mod's or SCR

AQMD BACT Guidelines

NOx, CO and VOC emission levels for stationary engines that are required by AQMD's non-major source BACT guidelines are shown in Table 12. As indicated in the table, these limits are usually met by rich-burn engines with larger TWCs, along with the air-to-fuel ratio controller (AFRC). Lean-burn engines generally come with low-NOx combustion modifications built into the engine by the manufacturer to reduce the emissions part way, and then use SCR plus oxidation catalyst to reduce emissions to BACT levels. Also shown in the table are apparent pollutant reductions achieved by these technologies, based on the typical uncontrolled emission levels shown in Table 9.

Additional information about SI engine control technologies is found in Appendix D.

Table 12. AQMD BACT Guidelines for Stationary Engines at Non-Major Polluting Facilities

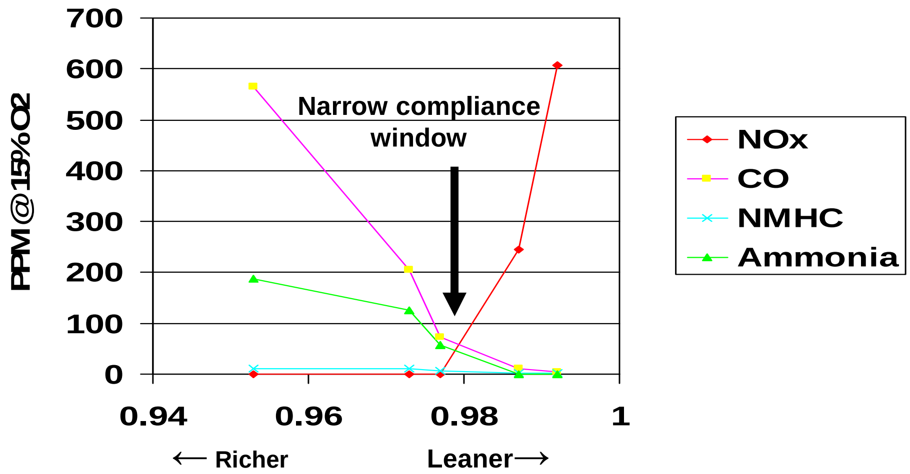
	PPMVD, corrected to 15% O2				Apparent Reduction by Control Technology	
	Uncontrolled Emission		BACT			
	Rich-Burn	Lean-Burn	Rich-Burn (NSCR)*	Lean-Burn (SCR + CatOx)	Rich-Burn (NSCR), %	Lean-Burn (SCR + CatOx), %
NOx	590	1090	10	9	98+	99+
CO	1629	136	69	33	95+	75+
VOC	23	91	29	25	---	73+

*Assuming engine is 30% efficient (HHV basis).

Rich-Burn Engine Control Technology Issues

When a rich-burn engine with a TWC and AFRC is properly tuned and source tested, excellent emission reductions are achieved. The following figure[13] demonstrates the emissions versus the Lambda value (λ)[14]. There is a narrow window of λ, or air/to fuel ratio, in which all pollutants are minimized. When the engine operates about 1% too lean, NOx shoots up to 600 ppmvd @ 15% O2. When the engine operates about 2 ½% too rich, CO increases to about 550 ppmvd and ammonia increases to about 200 ppmvd. In this rich condition, the TWC is converting NOx to ammonia instead of N2.

Figure 6. Three Way Catalyst Controlled Engine Emissions vs. Lambda



It is the job of AFRC and O2 sensor to maintain the engine λ at the right point. In order to keep all emissions low, the λ window for the engine in the figure is only about 0.5% or ± 0.25%.

Before the once every three year source test is conducted, engines operators assure that engines are in good operating condition and properly tuned to the correct air-to-fuel ratio.

Engines require a lot of maintenance in a three year period. On a engine used 24/7, it is typical to require an oil change once a month, and tune-ups every two months, including new spark plugs and O2 sensors. The current rule requires no checking of emissions during these numerous engine maintenance operations.

Aside from normal maintenance, a lot can go wrong with an engine or its emission control system that can cause excess emissions, including:

[13] Data are from Reference 14.

[14] Lambda (λ) is the ratio of the actual air/fuel ratio divided by the stoichiometric air/fuel ratio. When λ is less than 1.0, the engine is running rich, or with less air than is required for exact stoichiometric combustion.

- A bad spark plug
- A faulty spark plug wire
- A failed O2 sensor
- A O2 sensor for which the mV signal has drifted
- A catalyst that has plugged due to ash from lubrication oil blowby
- A catalyst that has become deactivated due to poisoning from ash blowby or excess exhaust temperature
- A catalyst that degrades from vibration allowing bypassing of the catalyst
- A failed AFRC
- A AFRC that is not properly recalibrated after an O2 sensor replacement

The oxygen sensor is a critical component of the emission control system. Based on information from several sources, it appears that the O2 sensor set point that works upon initial startup will not be the proper set point as the O2 sensor ages[15]. In Reference 12, a leading manufacturer of AFRCs says "Unfortunately, as the EGO sensor (O2 sensor) ages, the rich voltage response diminishes, rendering an ambiguous calibration reference. For this reason, the closed loop control target must be periodically re-calibrated in reference to the exhaust stack emissions to maintain compliance." In other words, the emissions must be periodically measured and the oxygen sensor set point readjusted.

The information in Appendix C also demonstrates the emissions problems caused by the drift in the signal from an oxygen sensor.

Stationary Engine Versus Automotive Engine Controls

Automotive engines in new vehicles have a reputation of achieving remarkably low emissions and doing so reliably with minimal maintenance and no air-to-fuel ratio (AFR) adjustments. Why isn't the same true for stationary engines? The reason is there are many differences between automotive and stationary engines:

- The automobile manufacturer certifies the engine/TWC/AFRC package to achieve required emission levels. The stationary rich-burn engine manufacturer produces an uncontrolled engine that is retrofitted by an AFRC and TWC from a variety of other manufacturers.
- Automotive engines are required to have on-board diagnostics (OBD) to detect many different engine and emissions problems, and trigger and engine malfunction light to alert the driver. Stationary engines aren't required to have any diagnostics.
- Automobile engines fuel systems and emission controls are more sophisticated than stationary engines. The automobile engine uses a separate fuel injector for each cylinder, while the stationary engine generally uses a single carburetor for up to eight cylinders in the same bank. The automotive engine has heated oxygen sensors both upstream and downstream of the TWC. Although some AFRCs are available with upstream and downstream sensors, most controlled stationary rich-burn engines have cheaper unheated sensors and only upstream of the TWC.

[15] See Reference 11, Chapter Six for a discussion of oxygen sensor aging.

- Automobile engines use a different approach to controlling the AFR than stationary engine AFRCs. Stationary engine AFRCs (Compliance Controls, Miratech, Woodward, Altronic, Azonix-Dynalco, Continental, Gill, Waukesha) use the upstream O2 sensor to try to maintain a constant AFR (actually a constant O2 sensor output in the vicinity of 750 millivolts [mV] within the narrow range of less than 0.5% that is necessary simultaneously control NOx, CO and NMHC to low levels. Rather than maintain a fixed AFR, automotive engines' AFR dithers around stoichiometric. The upstream O2 sensor output cycles from about 200 to 700 mV. By comparing the upstream and downstream O2 sensor outputs, which behave very differently, the health of the catalyst is determined by measuring the oxygen storage capacity of the catalyst. This is how they meet the OBDII requirement to detect a catalyst problem that results in an emission exceedance.[16] Stationary engine AFRCs (Altronic, Gill, Waukesha) without downstream O2 sensors can't diagnose problems like automotive engines can. Stationary engine AFRCs that have upstream and downstream sensors try to maintain the upstream O2 sensor in a narrow range without dithering. Therefore, they can not use the same means as automotive engines to diagnose malfunctions. None of the stationary AFRC or engine manufacturers have demonstrated that they can reliably comply with emission limits over the life of the engine or detect malfunctions like auto manufacturers are required to do.
- Another major difference is the fuel. While autos primarily use gasoline, most stationary engines use natural gas. One might think this is an advantage for stationary natural gas engines, but for rich-burn engines there are disadvantages with natural gas. Natural gas has a narrower window of AFR than gasoline where high control efficiencies of NOx, CO and HC are simultaneously achieved.[17] Also, the presence in natural gas engine exhaust of hydrogen and methane, which don't occur in gasoline exhaust, causes shifts in oxygen sensor output.[18] The Honda Motor Company found this to be such a problem that they use a specially designed upstream oxygen sensor to deal with the hydrogen-induced lean shift and another specially designed oxygen downstream sensor to deal with the methane-induced rich shift in their compressed natural gas fueled Civic GX[19] that meets Super Ultra Low Emission Vehicle (SULEV) standards. Stationary natural gas engines usually use ordinary unheated oxygen sensors designed for gasoline engines that Honda rejected.

Rich-Burn Engine Demonstration Projects

The Rule 1110.2 Industry Stakeholder Work Group, in cooperation with AQMD, conducted some projects to demonstrate that modern AFRCs could: control rich-burn engines to comply with Rule 1110.2 and BACT emission limits; and alarm operators when there are excess emissions. Results of the projects are summarized in Appendix E. The projects did not achieve the desired results. They demonstrated that modern AFRCs are not adequate and that additionally periodic monitoring is needed.

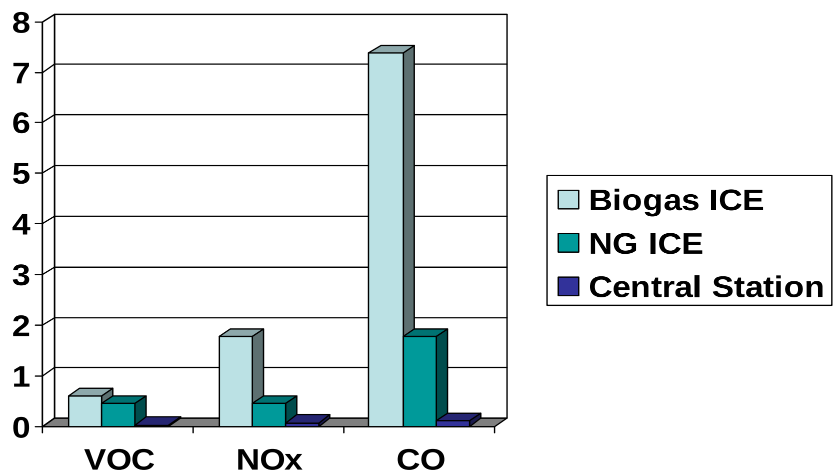
[16] Reference 11, Chapter 9.
[17] Reference 11, pgs. 280-281.
[18] Reference 11, pgs. 277-231.
[19] Reference 13

BIOGAS ENGINE EMISSIONS AND CONTROL TECHNOLOGIES

Biogas (digestor or landfill gas) engines are a special case. The engines are generally larger 4-stroke, lean-burn engines very similar to natural gas engines. Because the facilities have argued that contaminants in the fuel, like siloxane, are incompatible with catalytic after-treatment devices, biogas engines have generally not been required to install oxidation catalysts and SCR units that natural gas engines use. As a result, biogas engine emissions are the highest of all engines, even higher that a diesel engine with BACT.

The following figure demonstrates that the emissions from biogas engines, even when complying with BACT, far exceed natural gas (NG) engines and large central generating stations.

Figure 7. BACT for Biogas ICEs, NG ICEs vs. Central Generating Station BACT (lbs/MW-hr)



However, recent developments indicated that new technologies may allow emissions as low as with natural gas engines. Landfills in City of Industry and Brea have installed fuel gas treatment equipment to remove the contaminants and allow catalytic controls. Both have oxidation catalysts, while the City of Industry has also installed SCR for NOx control. There are also non-catalytic controls available. A selective non-catalytic NOx/VOC and CO control device by NOxTech has been installed on a landfill gas engine in Woodville, California. Landfills in Italy have installed engines with CL.AIR® non-catalytic VOC/CO control devices, both available from Jenbacher, part of GE Energy.

DIESEL ENGINE EMISSIONS AND EMISSION CONTROL TECHNOLOGIES

U.S. EPA's AP-42[20] lists uncontrolled industrial diesel engine emissions in terms of g/hp-hr as 14.0 NOx, 3.03 CO, and 1.12 VOC. Since 1996, nonroad diesel engines have been regulated at

[20] U.S. EPA AP-42 Compilation of Air Pollution Emission Factors, Table 3.3-1.

the federal and state levels through a certification program requiring that the manufacturers certify their engine models to meet certain emission standards, which become progressively more stringent over time. California's nonroad emission standards are the same as the federal nonroad standards. The nonroad emission standards for gaseous pollutants are shown in Table 13. The Tier 4 engines over 75 hp would comply with Rule 1110.2, but they will not be available until 2014.

Table 13. U.S. EPA Nonroad Diesel Gaseous Emission Standards—NOx or (NOx+NMHC)/NMHC/CO (g/Bhp-hr)

Engine Bhp	Tier 1	Tier 2	Tier 3	Tier 4 Interim	Tier 4 Final
50 to <75	1998 6.9 -- --	2004 (5.6) -- 3.7	2008 (3.5) -- 3.7		2012 (3.5) 3.7
75 to <100	1998 6.9 -- --	2004 (5.6) -- 3.7	2008 (3.5) -- 3.7	2012 2.6 0.14 3.7	2015 0.3 0.14 3.7
100 to <175	1997 6.9 -- --	2003 (4.9) -- 3.7	2007 (3.0) -- 3.7	2012 2.6 0.14 3.7	2015 0.3 0.14 3.7
175 to <300	1996 6.9 1.0 8.5	2003 (4.9) -- 2.6	2006 (3.0) -- 2.6	2011 1.5 0.14 2.6	2014 0.3 0.14 2.6
300 to <600	1996 6.9 1.0 8.5	2001 (4.8) -- 2.6	2005 (3.0) -- 2.6	2011 1.5 0.14 2.6	2014 0.3 0.14 2.6
600 to <750	1996 6.9 1.0 8.5	2002 (4.8) -- 2.6	2005 (3.0) -- 2.6	2011 1.5 0.14 2.6	2014 0.3 0.14 2.6
≥750	2000 6.9 1.0 8.5	2006 (4.8) -- 2.6		2011 2.6 0.3 2.6	2015 2.6 0.14 2.6

Note: ppmvd@15%O2 = g/Bhp-hr x (%EFF_{HHV}/100) / 1.15 x F (F= 253 for NOx, 415 for CO, 727 for VOC as methane)

Add-on control technologies that are suitable for diesel engines include SCR for NOx and oxidation catalysts for reduction of CO and VOC. Both of these technologies have been successfully applied to diesel engines. SCR involves injection of urea or ammonia into the flue gas upstream of the catalyst and results in emissions of small amounts of unreacted ammonia. Application of these technologies to a large Tier 1 diesel engine located at a ski resort in the AQMD achieved the NOx, CO and VOC emissions shown in Table 14. Assuming that the engine was designed for emissions to be approximately 20% below the Tier 1 standards, the apparent emission reductions achieved by the technologies are 90% for NOx, 99% for CO and 74% for VOC. Because of the high costs of the add-on control equipment for a diesel engine, compared to a SI engine, few diesels were retrofitted to comply with Rule 1110.2. Some became subject to the RECLAIM program, some were exempted from Rule 1110.2 and others were removed from service.

Table 14. Emission from Diesel Engine at Snow Summit Ski Resort (A/N 418235)

	Concentration in Exhaust Gas, ppmvd @ 15% O2	**Emission Rate, g/Bhp-hr**	**Tier 1 Emission Standard, g/Bhp-hr**	**Apparent Reduction Based on Uncontrolled Level = Tier 1 Less 20%, %**
NOx	45	0.546	6.9	90
CO	5	0.037	8.5	99
VOC	49	0.21	1.0	74
Ammonia	0.6	--	--	--

Emulsified fuel is another technology that can be applied to a stationary diesel engine. Emulsified fuel contains water, which has been blended into the fuel using appropriate blending equipment and an additive to create a stable mixture. Separation of the water can, however, occur if the fuel is in storage for too long. Presence of water in the fuel improves combustion while also lowering the flame temperature. It has been applied primarily to on-road and nonroad diesel engines and primarily for reduction of particulate emissions. However, it reduces NOx by only 10-20%[21].

Although SOx and PM emissions are not addressed by Rule 1110.2, SOx emissions are now well controlled with ultra low sulfur diesel fuel (< 15 ppm by weight) required by Rule 431.2. PM is also well controlled by diesel particulate filters.

OTHER TECHNOLOGY OPTIONS

For some stationary engines affected by the proposed Rule 1110.2 amendments, other options may be better than adding control equipment to the existing engine to bring the engine into compliance with the rule. One option for engines that drive pumps or compressors is to replace

[21] http://www.epa.gov/region1/eco/diesel/retrofits.html#doc

the engine with an electric motor. Most operators that choose an engine instead of an electric motor did so because of the lower energy cost of natural gas versus electricity. However, due to recent increases in natural gas costs, and the additional costs for engines such as maintenance, permits and source testing, and emission fees, electric motors are now a more attractive option.

For ICE electrical generators, operators may choose to replace the engines with cleaner technologies such as fuel cells, solar photovoltaic systems, or gas turbines. Or they could simply decide to buy the clean electric power available from their electric utility.

CHAPTER 4: PROPOSED AMENDMENTS

INTRODUCTION

EXEMPTIONS - SUBDIVISION (H)

REQUIREMENTS - SUBDIVISION (D)

COMPLIANCE – SUBDIVISION (E)

MONITORING, TESTING AND RECORDKEEPING – SUBDIVISION (F)

DEFINITIONS – SUBDIVISION (C)

INTRODUCTION

The basic purposes of the proposed amendments are to: 1) improve the compliance record of engines with better monitoring, recordkeeping and reporting; and 2) achieve further emission reduction based on the cleanest available technologies. A summary of the proposed amendments follows. They are discussed in order of importance rather than in rule subdivision order.

EXEMPTIONS – SUBDIVISION (H)

This is the last subdivision in the rule, but it is useful to discuss it first so that it is understood up front what the exemptions are.

Emergency, Flood Control and Fire Fighting Engines

The current rule exempts several types of engines from the subdivision (d) emission limits. Paragraph (h)(2) exempts emergency engines while paragraph (h)(3) exempts fire fighting and flood control engines. The proposed amendments do the following: combine the exemptions into paragraph (h)(2); require all of these engines to operate less than 200 hours/year; and require that permits conditions specifically limit the annual operating hours.

Justification

Engines used for emergencies, fire fighting and flood control are all limited use engines, but fire fighting and flood control engines were not limited to 200 hours/year as were other emergency engines. The proposed amendments remedy this by limiting them all to 200 hours/year.

A review of the stationary, non-emergency AQMD engine permits found 68 permits that were actually for emergency, fire fighting or flood control engines, but the permits did not limit the operation to any particular use or limit annual hours of operation. Neither operators nor AQMD inspectors may know from the permit that the engines are limited in their operation. The proposed amendment requires that the operating hours on the permit be specifically limited to 200 hours/yr or less. Operators will have to apply for a simple change of permit conditions to qualify for the exemption.

Start up Exemption

The current rule has no exemption during engine startups. The proposed amendments in paragraph (h)(12) will provide an exemption from complying with the emission limits in the rule until emission controls reach operating temperature, but not longer than 15 minutes.

Justification

Catalytic controls such as TWC, SCR or oxidation catalysts are not effective until they reach a certain operating temperature. AQMD requested startup emission data from engines with CEMs to determine how much time is needed to achieve compliance. The response was limited, but it appears that catalysts can reach sufficient operating temperature within 15 minutes. AQMD would welcome any additional data that engine operators would care to submit.

REQUIREMENTS – SUBDIVISION (D)

Reduction of the Emission Concentration Limits

Subparagraph (d)(1)(B) currently limits NOx, VOC and CO concentrations to 36, 250 and 2000 ppmvd, respectively. The proposed amendments will reduce these limits by 2011 or 2012 to levels comparable to current BACT.

Table 15. Proposed Concentration Limits

CONCENTRATION LIMITS		
NO_x (ppm)[1]	VOC (ppm)[2]	CO (ppm)[1]
bhp ≥ 500: 36 bhp < 500: 45	250	2000
CONCENTRATION LIMITS EFFECTIVE JULY 1, 2010		
NO_x (ppm)[1]	VOC (ppm)[2]	CO (ppm)[1]
bhp ≥ 500: 11 bhp < 500: 45	bhp ≥ 500: 30 bhp < 500: 250	bhp ≥ 500: 70 bhp < 500: 2000
CONCENTRATION LIMITS EFFECTIVE JULY 1, 2011		
NO_x (ppm)[1]	VOC (ppm)[2]	CO (ppm)[1]
11	30	70

1 Corrected to 15% oxygen on a dry basis and averaged over 15 minutes.

2 Measured as carbon, corrected to 15% oxygen on a dry basis and averaged over 30 minutes.

<u>Justification</u>
There are several reasons why the existing emission concentration limits should be reduced.

- The 2007 Draft AQMP shows that addition NOx and VOC emission reduction are necessary to achieve the PM2.5 and ozone standards. The proposed reductions, which are approximately equivalent to BACT, will help achieve those standards.
- The proposed VOC limits will not just reduce PM2.5 ozone precursor emissions. They will also reduce hazardous air pollutants such as formaldehyde. Although AQMD is close to being declared in attainment of the CO ambient air quality standards, the reduced CO limits have other benefits. Reducing CO emissions from rich-burn engines will reduce ammonia

emissions, a PM2.5 precursor, caused when the engines operate too rich. Also, CO is a mild ozone precursor.

- The proposed future NOx, VOC and CO limits are achievable for rich-burn engines with the same technology currently in use: TWCs with an automatic air-to-fuel ratio controller (AFRC) with an oxygen sensor. Many rich-burn engines already meet BACT limits. Some engines may need to replace their catalyst or add another layer of catalyst.
- The proposed future NOx, VOC and CO limits are also achievable by lean-burn engines, which inherently have lower CO emissions than rich-burn engines. lean-burn engines already meet BACT limits.
- The Draft 2007 AQMP control measure CM #2007MCS-01 calls for stationary facilities to modernize their equipment to achieve BACT emission levels. The proposed 2014 limits are comparable to current BACT requirements for new rich-burn and lean-burn engines. They are also the same limits found in Table I of the current rule. Operators will have several choices to comply: retrofit emissions controls on existing engines, or use cleaner technologies such as, fuel cells, microturbines, gas turbines or zero-emission electric motors.

Revisions to the Efficiency Correction for Stationary Engines

The current rule in subparagraph (d)(1)(C) allows most stationary engines to upwardly adjust the ppmvd emission limit in Table III based on the actual engine efficiency or the manufacturer's rated efficiency. More efficient engines are allowed higher ppmvd limits.

The proposed amended subparagraph (d)(1)(C) limits the efficiency correction to biogas-fired engines (landfill or digestor gas), requires that the correction be based on actual efficiency from ASME test procedures, requires the engines to use at least 90% biogas on an annual basis, and requires the corrected emission limits to be stated on the operating permit.

Justification

The efficiency correction has led to a lot of confusion when determining what the emission limit should be. Actual engine efficiencies are difficult to determine, especially for engines driving pumps or compressors, where there is generally no measurement of work output. Manufacturer's efficiency specifications are often misinterpreted because they do not include auxiliary loads such as cooling fans, or are quoted based on lower heating value when they need to be based on higher heating value of the fuel. The emission limits after the efficiency correction are often not stated on older permits, leaving operators, AQMD enforcement personnel and source testing contractors unsure of the emission limits. When contractors test engines for compliance they usually just report the uncorrected limits of Rule 1110.2 because they don't know the actual or specified engine efficiency.

The efficiency correction is proposed to be continued for digestor gas and landfill gas fired engines because those engines have had some difficulty complying with the current limits, and their options for controls are more limited than for natural gas engines. However it is contingent on the engine using at least 90% of digestor or landfill gas, based on the higher heating value of the fuels, on an annual basis. New biogas engines emit about four times more than new natural gas fired engines. Some biogas engine operators have increased their electricity production and emissions by burning significant quantities of natural gas in addition to the available biogas. If operators want to burn natural gas, they should do it with the better emission controls available for natural gas engines.

Emission Standards for Biogas Engines

In addition to allowing biogas engines to continue to use an efficiency correction factor, the following emission concentration limits are proposed for biogas-fired engines:

Table 16. Proposed Concentration Limits for Biogas Engines

CONCENTRATION LIMITS FOR LANDFILL AND DIGESTOR GAS-FIRED ENGINES		
NO_x (ppm)[1]	VOC (ppm)[2]	CO (ppm)[1]
bhp $\geq$ 500: 36 x ECF[3] bhp < 500: 45 x ECF[3]	Landfill Gas: 40 Digestor Gas: 250 x ECF[3]	2000
CONCENTRATION LIMITS EFFECTIVE JULY 1, 2012		
NO_x (ppm)[1]	VOC (ppm)[2]	CO (ppm)[1]
11	30	70

1 Corrected to 15% oxygen on a dry basis and averaged over 15 minutes.

2 Measured as carbon, corrected to 15% oxygen on a dry basis and averaged over 30 minutes.

3 ECF is the efficiency correction factor.

Initially, only the VOC limit for landfill gas-fired engines would change, to be consistent with other current requirements. In 2012, the emissions limits would drop to current BACT levels, just as is proposed for other engines.

<u>Justification</u>

Rule 1150.1 currently requires landfill gas-fired engines to reduce NMOC (non-methane organic compounds) emissions by 98% or to 20 ppmvd as hexane, corrected to 3% O2. Engines generally comply with this requirement by meeting the 20 ppmvd limit, rather than the more stringent 98% destruction efficiency. 20 ppmvd as hexane, corrected to 3% O2 is equivalent to 40 ppmvd as carbon, corrected to 15% O2, the proposed limit.

The proposed 2012 limits are the same as found in Table I of the rule, and are approximately equivalent to current BACT for natural gas ICEs. As discussed in Chapter 3, control technologies are being developed and demonstrated that allow compliance with the proposed limits. Biogas engines will have another year or two to comply than other engines. The options for compliance with the biogas engines will be to: install biogas cleanup equipment that will enable use of catalytic after treatment controls, install non-catalytic after treatment controls, or replace the ICEs with cleaner technologies such as microturbines or fuel cells.

Emission Standards for New Non-Emergency Electrical Generation Engines

New non-emergency are proposed in subparagraph (d)(1)(F) to be subject to the emission standards in the following table.

Table 17. Proposed Emission Limits for New Electrical Generating Engines

EMISSION STANDARDS FOR NEW ELECTRICAL GENERATION ENGINES	
Pollutant	**Emission Standard (lbs/MW-hr)**
NOx	0.07
CO	0.10
VOC	0.02

These emission standards do not apply to digestor or landfill gas-fired engines or engines installed or issued a permit to construct before June 1, 2007.

For engines that do not produce combined heat and power (CHP), the emission standards are based on the net electrical megawatt-hours (MW_e-hrs) produced. CHP (also know as cogeneration) engines may also take credit for the thermal megawatt-hours (MW_{th}-hrs) of useful heat produced, with one MW_{th}-hr for each 3.4 million Btus. The thermal energy could take the form of hot water, steam or other medium.

For CHP engines, the operator will choose short-term emission limits in lbs/ MW_e-hrs that the engine must meet at all times. The operator will also choose an annual electrical energy factor (EEF), such that when the short-term emission limit is multiplied by the annual EEF, the result does not exceed the values in the above table. The EEF is the annual net electrical energy produced divided by the sum of the electrical and thermal energy produced. The operator will have to also meet the annual EEF limit.

<u>Justification</u>
As of January 1, 2007, CARB already enforces the above standards for distributed generation equipment that do not require local district permits. The standards are based on the emissions from large new central generating stations with BACT. Since large and small electrical generators are already required to meet these standards, the proposed standards will simply extend the same requirements to ICEs that require AQMD permits. This was the goal of SB1298 as previously described in Chapter 1.

The thermal energy recovered varies seasonally and diurnally. At times it may be zero. It would not be fair to require the CHP system to meet the CARB emission standards at all times. The proposed requirements allow the CHP operator to meet the CARB standards by correcting the emissions based on the annual average of the EEF. For example, if a CHP engine produces, on an annual average, one MW-hr of thermal energy for each MW-hr of electrical energy, then the annual EEF would be 0.5. The operator could choose a short-term NOx limit of 0.14 lbs/MW_e-hr, because 0.14 lbs/ MW_e-hr x 0.5 = 0.07 lbs/MW-hr.

Air-to-Fuel Ratio Controllers

The current rule doesn't require an air-to-fuel ratio controller for ICEs. The proposed amendments require ICEs without a CEMS to install an air-to-fuel ratio controller (AFRC) with an oxygen sensor and feedback control.

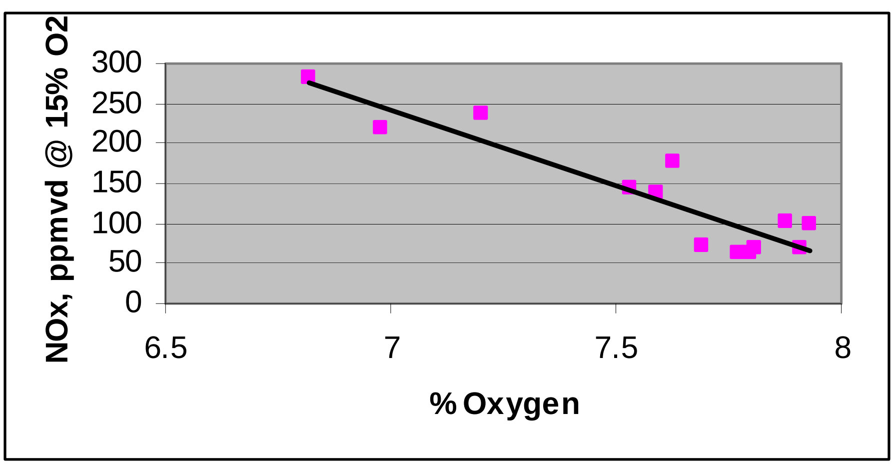
Justification

For ICEs that do not have a CEMS to detect non-compliance, an AFRC is the most important part of the control system for maintaining compliance of both rich-burn and lean-burn engines. Changes in load, air temperature and humidity, and fuel quality can affect the air-to-fuel ratio. With the use of the oxygen sensor, the AFRC can adjust the air to fuel ratio to a set point that can achieve compliance with emission limits.

Nearly all rich-burn engines have AFRCs, because AQMD Engineering has been requiring them when the engines are permitted. In order to meet emission limits, the air-to-fuel ratio for rich-burn engines with TWCs must be maintained within a range of about ½ percent.

The air-to-fuel ratio is less critical, but still important for lean-burn engines. An EPA verification report (Reference 7) found that an AFRC reduced NOx emissions by an average 30% from a low-NOx, lean-burn engine, when fuel quality was steady. But additional data were obtained from the author when the pipeline natural gas heating value suddenly increased about 8%. Without the AFRC in operation, the engine operated with a lower air-to-fuel ratio, causing the % oxygen in the exhaust to drop from 7.8% to 6.8%. This increased NOx emissions by up to 300%. Figure 8 shows significant effect than % O2, and air-to-fuel ratio, have on lean-burn engines.

Figure 8 – NOx versus % Oxygen in Exhaust for a Caterpillar Lean-Burn Engine



AQMD natural gas supplies are expected to become more variable in the future as liquefied natural gas (LNG) begins to be delivered to AQMD starting around 2008. Many LNG supplies are reported to have significantly higher heating value and Wobbe Index[22] than current supplies. Therefore, the need for AFRCs will be even greater than it is now.

Portable Engines

Staff proposes to remove the emission limits and related requirements for portable engines in subparagraph (d)(2)(A) and add a reference to the CARB-adopted, portable diesel ATCM and the Large Spark-Ignition Fleet Requirements, which some portable engines are subject to.

Justification
The current rule in paragraph (d)(2) seems to require portable engines to meet the emission limits in Tables IV and V. It also seems to require portable engines to meet the most stringent emission standard in Title 13 of the CCR by 2010 (currently Tier III for diesels). However, the exemption in paragraph (h)(10) exempts all nonroad engines from these requirements. The definitions in the current rule for non-road engine and portable engine are practically the same, which results in all portable engines actually being exempt from the portable engine emission requirements.

At the time of the 1997 amendments to the rule, it was interpreted that nonroad engines were only those manufactured after November 15, 1990 or later, which would make older portable engines subject to rule requirements, but this was not actually stated in the rule language. By a plain reading of the exemption for nonroad engines, all portable engines are exempt. Also, as explained in the Background section, EPA has clarified that the date of manufacture is irrelevant to whether it is nonroad. Therefore, to simplify the rule and eliminate the confusion it causes, staff proposes to remove the emission limits and related requirements for portable engines in subparagraph (d)(2)(A). However, some portable engines are subject to subject to either the portable diesel ATCM or the Large Spark-Ignition Fleet Requirements adopted by CARB. Therefore, a reference to these requirements is proposed for the benefit of portable engine operators.

COMPLIANCE – SUBDIVISION (E)

The unnecessary existing paragraphs (e)(1) and (e)(3) are proposed for deletion. New paragraphs (e)(3) through (e)(5) propose compliance schedules for non-agricultural engines required to meet the future emission limits, the stationary engine CEMS requirements, and the I&M plans. The schedules will allow time for review and approval of applications for permits to construct, CEMS application, and I&M plan applications.

New engines will be required to comply with the new CEMS and I&M requirements when they begin operation.

MONITORING, TESTING AND RECORDKEEPING – SUBDIVISION (F)

The primary focus of the proposed amendments in this subdivision is to improve the poor compliance record of stationary engines, as explained in Chapter 1 of the staff report.

[22] Emissions are generally better correlated with Wobbe Index than heating value. Wobbe Index is the heating value divided by the square root of the specific gravity of the fuel.

Additional CEMS Requirements

The existing subparagraph (f)(1)(A) requires 1000 hp engines and larger, that produce two million bhp-hrs per year or more to have a NOx CEMS. The proposed amendments, effective on July 1, 2008, add CO emission monitoring back into the rule in subparagraph (f)(1)(A), as it was before the 1997 amendment. In addition, the CEMS requirement will be extended to stationary engines at facilities with multiple engines at the same location (within 75 feet of each other) that have a cumulative stationary engine horsepower rating of 1000 bhp or more. To reduce the cost, the CEMS can be time-shared between all engines < 1000 hp.

Justification
Before the rule was amended in 1997, CO monitoring was required for 1000+ hp engines. However, as explained in the background, compliance with CO emission limits is as much a problem as is NOx compliance. Therefore, it is necessary to put CO monitoring back into the rule. CO monitoring can be added to a NOx CEMS at a relatively small additional cost.

It is not uncommon for facilities to install multiple ICEs side-by-side, each rated just under 1000 hp, in order to avoid the rule requirement for a CEMS. However, a CEMS is the best possible way to assure continuous compliance of engines with the rule or BACT emission limits. The ability to time-share the CEMS between engines < 1000 hp will reduce the CEMS cost but still result in the detection of engine or control equipment problems in a reasonable period of time.

A 1000 hp engine, or a group of engines rated at 1000 hp, are a very significant emission source. Based on the EPA uncontrolled emission factor in Table 9, the NOx potential to emit of a 1000 hp engine ranges from 77 to 143 tons/year. This is far in excess of the 10 ton/yr major source threshold. A 1000 hp engine, burning 8 MMBtu/hr of natural gas, emits as much NOx as a 126 MMBtu/hr uncontrolled boiler. The CEMS requirement for boilers starts at only 40 MMBtu/hr.

Source Testing for Stationary Engines

The current requirement of subparagraph (f)(1)(C) is that emission testing be done once every three years. The proposed amendments increase the frequency of source testing every two years, or 8,760 hours, whichever occurs first.

In addition, the following source testing reforms are proposed:

- Emissions must be tested at for at least 15 minutes at peak load and for at least 30 minutes during normal operation. The source test can't just be at one load under steady state conditions, unless that is the typical duty cycle. In addition NOx and CO must be tested for at least 15 minutes at actual peak load and actual minimum load.
- Pretests to determine if the engine needs repairs will not be allowed.
- The test must be conducted at least 40 operating hours or one week after any engine tuning or maintenance.
- If a test is started and shows non-compliance, it may not be aborted to allow engine tuning or repairs. The test must be completed and reported.
- A source testing contracter approved by AQMD must be used.
- A source test protocol must be submitted and approved by the District at least 60 days before the test is conducted. The protocol will also identify the critical parameters that

will be measured during the test, as required by the Inspection and Maintenance Plan (discussed later).

- AQMD must be notified of the test date.
- The test report must be submitted to AQMD within 45 days of the test date. This will assure that noncompliance will be reported.
- The operator must provide source testing facilities including sampling ports in the stack, safe sampling platforms, safe access to sampling platforms, and utilities for test equipment.

Justification

Rule 1110.2 originally required source testing every year, until it was amended in 1997. The once every two years proposal is consistent with the CARB RACT/BARCT document recommendation and an EPA requirement to make the rule approvable.

All of the proposed reforms are needed to assure that source tests are properly conducted, representative of actual operation, and reviewed by AQMD. The problems of the current rule and proposed solutions are discussed as follows:

- Engine emissions can vary significantly at different operating loads and if actual loads are varying. The current rule allows operators to operate at a steady-state load, and at only one load. This will not detect problems under other actual operating conditions. The amendments will make the source test more representative of actual conditions. A minimum 30-minute, normal operation test is needed for the VOC test method. The peak and minimum load tests for NOx and CO only can be done for only 15 minutes because their test methods are amenable to shorter periods.
- Operators can now pretest and do an engine tune up to assure the engine is operating properly before the source test. This is why source tests always show compliance, while unannounced AQMD tests often show noncompliance. The proposed amendments require the engine to be tested as is.
- Operators can abort a source test that shows non-compliance, make repairs to the engine or control equipment, and restart the test. The existing violation is covered up.
- Operators can use unqualified testing companies. AQMD has a Laboratory Approval Program and maintains a list of approved source testing contractors.
- Engine operators don’t have to notify AQMD of the date of a scheduled test. This prevents AQMD from observing a test to assure it is properly conducted.
- The current rule requires neither a source test protocol nor the test report to be reviewed by AQMD. AQMD Engineering requires this for the source test done before a permit to operate is issued, but the rule doesn’t require it for subsequent tests. The protocol will be necessary to assure that the proposed reforms are known and planned for each test. Non-compliant test reports can be filed away without notifying AQMD of the excess emission.
- Often overlooked are the requirements of AQMD Rule 217 – Provision for Sampling and Testing Facilities which requires that operators provide needed and safe sampling facilities. These are necessary for the scheduled source tests, as well as for the unscheduled tests by AQMD inspectors.

Inspection and Monitoring (I&M) Plan for Stationary Engines

An I&M Plan will be added to the rule in subparagraph (f)(1)(D). Except for engines monitored by a CEMS, stationary engine operators will submit to AQMD for approval an I&M Plan to assure continued compliance of the engines between source tests. The I&M Plan will include procedures for:

- Establishing acceptable ranges for control equipment parameters and engine operating parameters that source testing or portable analyzer monitoring has shown result in pollutant concentrations within the rule limits. The required parameters include, but are not limited to: engine load; oxygen sensor voltage output or equivalence ratio (AFRC may use either); for rich-burn engines with TWCs, catalyst inlet and outlet temperatures and the temperature change across the catalyst; and for lean-burn engines with selective catalytic reduction, the reactant flow rate (ammonia or urea).
- Procedures for a diagnosing emission control malfunctions alerting the owner/operator to the malfunction. A malfunction indicator light and audible alarm are required.
- Weekly, or every 150 hours, emissions checks by a portable NOx, CO and O2 analyzer. The schedule can be reduced to monthly, or every 750 hours if three consecutive weekly tests show compliance. If the monthly test is non-compliant or the oxygen sensor is replaced, then weekly tests must be resumed. In order to representative of actual operation, the test will be conducted at least 72 hours after any engine or control system maintenance or tuning. The portable analyzer will be calibrated, maintained and operated in accordance with the manufacturer's specifications and recommendations and the AQMD's "Protocol for the Periodic Monitoring of Nitrogen Oxides, Carbon Monoxide, and Oxygen from Sources Subject to South Coast Air Quality Management District Rule 1110.2"
- At least daily recordkeeping of monitoring data and actions required by the plan, including formats of the recordkeeping;
- Preventive and corrective maintenance, and their schedules;
- For rich-burn engines with TWCs, an emission check will be required when an oxygen sensor set point must be readjusted, or within 24 hours after a new oxygen sensor is installed, to establish new set points at minimum, maximum and midpoint loads.
- Reporting noncompliance to the Executive Officer. If an engine owner/operator finds an engine to be operating outside the acceptable range for control equipment parameters, engine operating parameters, engine exhaust NOx, CO, VOC or oxygen concentrations, the owner/operator will: report the noncompliance within one hour in the same manner required by paragraph (b)(1) of Rule 430 – Breakdowns; immediately correct the noncompliance or shut down the engine within 24 hours or the end of an operating cycle, in the same manner as required by subparagraph (b)(3)(iv) of Rule 430; and comply with all requirements of Rule 430 if there was a breakdown.
- Recordkeeping, including formats of the recordkeeping.
- Plan revisions. Before any change in I&M plan operations can be implemented, the revised I&M plan will have to be submitted to and approved by the Executive Officer.

<u>Justification</u>
The CARB report "Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Spark-Ignited Internal Combustion

Engines" found that source testing alone was not sufficient to assure ICE compliance, and recommended that ICE operators prepare and implement an I&M Plan to improve compliance. EPA also requires an I&M Plan to make the rule approvable.

As discussed in the Background section of this report, AQMD has also found major compliance problems with ICEs. Many of the proposed I&M Plan elements are based on the CARB recommendations. The I&M Plan will be the most important way of reducing emissions from ICEs. The I&M Plan will not be required of ICEs that have a CEMS, because the CEMS will detect non-compliance even better than the I&M Plan.

The identified parameters to be monitoring are the important ones for rich-burn and lean-burn engines. In lieu of CEMS data, they can be used to determine if there is a problem with the engine in between source tests or periodic emission checks with the portable analyzer. As previously explained the air-to-fuel ratio is important for both rich-burn and lean-burn engines.

For rich-burn engines, the catalyst inlet temperature must be limited to protect the catalyst from overheating. Also the catalyst oxidizes CO and VOC in exothermic reactions. A change in the delta T of the inlet and outlet of the catalyst can signal reduces catalyst activity. AFRCs typically monitor these parameters and are capable of alerting the operator to malfunctions.

Operators are required to inspect the engines, look for malfunctions, and record the necessary operating parameters at least daily. Alternatively, the engines may be monitored remotely. Some engines and AFRCs have the capability to be monitored remotely through an internet connection or phone line.

The oxygen sensor set points often need to vary depending on engine load, because of differences in emissions and catalyst temperatures. AFRCs are capable of multiple set points at different loads, although operators sometimes cut corners and use only one set point. The set points also need to be checked and changed when a new oxygen sensor is installed because as the sensor ages and output drifts, set points need to change. See Appendices C and E for additional discussion of this.

The weekly testing with a portable analyzer is an extremely important part of I&M plan. Portable analyzers capable of measuring NOx, CO and O2 are available from multiple manufacturers, easy to use, relatively inexpensive and capable of detecting emissions problems. One engine operator is currently required by the permit to operate to test two engines daily to assure compliance with BACT emission limits. Operators can purchase and operate the equipment or hire third parties to do the testing.

AFRC and engines manufacturers are working on improvements to control systems for rich-burn engines. If compliance is demonstrated in three consecutive weekly emission checks, without any adjustments to AFRC set points, then the testing can be reduced to monthly, or every 750 operating hours. By this means, good performing systems can benefit by less-frequent emission checks.

Only Title V facilities (major sources) are currently required to report deviations to AQMD. The proposed amendments extend this to other engine operators so that AQMD Enforcement staff can take the appropriate enforcement action. Enforcement discretion will apply depending on the frequency and severity of the deviations.

The proposed amendments reference the breakdown provisions of AQMD Rule 430, so that engine operators are aware of the protection from enforcement action if the requirements of the rule are met.

I&M Plan revisions will probably be necessary as operators learn how best to manage their engines. The rule provides a process to have AQMD approve those revisions.

Portable Analyzer Training

In order to assure that persons conducting the portable analyzer testing are properly trained to understand the equipment and the procedures for conducting testing, maintenance and calibration, subparagraph (f)(1)(G) requires persons to take a District-approved training program and obtain a certification issued by the District. AQMD intends to conduct the training.

Operating Log

Because dual-fuel engines may consume both liquid and gaseous fuels, proposed paragraph (F)(1)(E) is proposed to require fuel use of both fuels to be logged, instead of either fuel

New Non-Emergency Electrical Generating Engines

New monitoring procedures are required for the proposed emission standards for new, non-emergency, electrical generating engines. All such engines will be required to monitor: the net electrical output (MW_e-hrs) of the engine generator system, which is the difference between the electrical output of the generator and the electricity consumed by the auxiliary equipment necessary to operate the engine generator and heat recovery equipment; and the useful heat recovered (MW_{th}-hrs), which is the thermal energy recovered and put to an actual useful purpose.

Emissions in lbs/MW_e-hr must be calculated based on CEMS data, source tests, and weekly emission checks. Mass emissions will be calculated using an F factor method from EPA 40 CFR 60, Appendix A, Method 19, or other approved method. Because Method 19 does not directly address VOC and CO, necessary conversion factors are provided in the rule. An annual report is required to verify compliance with the annual EEF.

<u>Justification</u>
Output-based emission standards, which are based on production of something, are always more complicated than limits on stack emission concentrations. They require monitoring of emission concentrations, fuel use or exhaust flows, and the item produced. The benefit of an output-based emission standard is that it gives an advantage to more efficient processes.

DEFINITIONS – SUBDIVISION (C)

A new definition for "oxides of nitrogen" and revised definition of "approved emission control plan" are proposed to simply clarify the intent of the rule. New definitions for "net electrical energy", "rich-burn engine with a three-way catalyst", and "useful heat recovered" are necessary to support the new requirements previously discussed.

CHAPTER 5: IMPACT ASSESSMENTS AND LEGAL MANDATES

EMISSION IMPACTS

COST EFFECTIVENESS

COMPARATIVE ANALYSIS

DRAFT FINDINGS

EMISSION IMPACTS

The proposed amendments to Rule 1110.2 will have emission impacts on stationary, non-emergency engines. The 1990 staff report for proposed Rule 1110.2 estimated that Rule 1110.2 would reduce NOx emissions of 1,289 stationary, non-emergency engines from 28.0 tons/day to 2.9 tons/day.

Table 18 shows estimated allowable and excess emissions from all stationary, non-emergency engines in the district and also emissions in the future as the amended rule takes effect. As discussed earlier in the report, under Emissions Inventory, the current emissions were calculated based on fuel usage data, NOx concentration limits (or actual NOx emissions for RECLAIM NOx majors), and CO and VOC concentrations based on permit limits (for BACT engines) or source test data (for non-BACT engines). As also discussed there, excess emissions were estimated based on the results of unannounced compliance testing. The allowed emissions now and in the future were calculated based on the same fuel usage data, except that biogas engines are restricted to 10% natural gas beginning 6/1/2007, and concentration limits that apply or will apply to each engine at any point in time.

Table 18. Emissions from Stationary, Non-Emergency Engines (TPD)

	NOx	VOC	CO
Calculated Emissions Based on 2005 Survey	3.29	1.47	11.2
Estimated Excess Emissions	1.29	5.40	21.7
Total Calculated/Estimated Emissions	4.58	6.87	32.9
Allowed Emissions	3.70	3.77	57.8
Allowed Emissions 6/1/2007	3.52	3.45	54.6
Allowed Emissions 7/1/2012	2.15	0.97	3.99

As engines are brought into compliance with the initial requirements of the amended rule, substantial reductions of NOx, VOC and CO emissions should take place through elimination of excess emissions (by enhanced monitoring and I&M requirements), reduction of NOx and VOC concentration limits on most engines that now benefit from the efficiency factor provision in the rule, and reduction of natural gas usage in biogas engines. Further reductions in all three pollutants will take place as the concentration limits in the rule are reduced from 2010 to 2012.

COST EFFECTIVENESS

Cost effectiveness is still being evaluated by AQMD staff.

COMPARATIVE ANALYSIS

As required by Health and Safety Code Section 40727.2, the purpose of this analysis is to identify and compare any other AQMD or federal regulations that apply to the same equipment or source type.

National Emission Standards for Hazardous Air Pollutants

The RICE NESHAP was described in Chapter 1. Table F-1 in Appendix F provides a detailed summary and comparison of the key elements of PAR 1110.2 and the RICE NESHAP. The RICE NESHAP only regulates formaldehyde emissions or CO as a surrogate for hazardous air pollutants, and is more stringent than the current Rule 1110.2 limit on CO. However, it applies only to a few major sources. Rule 1110.2 is still necessary to regulate NOx, CO and VOC from engines.

New Source Performance Standards

The CIE NSPS was described in Chapter 1. Table F-2 in Appendix F provides a detailed summary and comparison of the key elements of PAR 1110.2 and the CIE NSPS.

The CIE NSPS only regulates new CI engines and is not as stringent as the Rule 1110.2 and AQMD BACT requirements for non-emergency engines. The CIE NSPS will require fire pump CIES to be certified to more stringent levels than AQMD currently requires. Rule 1110.2 is still necessary to regulate NOx, CO and VOC from existing and new engines.

The existing requirements, as well as the proposed amendments to Rule 1110.2, are not in conflict with federal regulations.

AQMD Rules Applying to Stationary Gaseous and Liquid-Fueled Engines

AQMD Rule 218 - Continuous Emission Monitoring, which was last amended on May 14, 1999, sets forth requirements for new, modified and existing continuous emission monitoring systems that include certification, development and implementation of a Quality Assurance/Quality Control Plan, recordkeeping and reporting. PAR 1110.2 requires ICEs with required CEMS to comply with Rule 218.

AQMD Rule 401 – Visible Emissions, which was last amended on November 9, 2001, prohibits the discharge of emissions into the atmosphere from any single source for period or periods aggregating more than three minutes in any one hour which will cause: a dark or darker shade as that of a number 1 on the Ringelmann chart, as published by the United States Bureau of Mines, or of an opacity equal or greater than number 1 on the Ringelmann chart.

AQMD Rule 431.1 – Sulfur Content of Gaseous Fuels, which was last amended on June 12, 1998, prohibits the sale and use natural gas with a sulfur content exceeding 16 ppm. Rule 431.1 also prohibits the sale and use of the following gases with a sulfur content exceeding: 150 ppmv in landfill gas; 40 ppmv in refinery gas, sewage digester gas and other gases.

AQMD Rule 431.2 – Sulfur Content of Liquid Fuels, which was last amended on September 15, 2000, prohibits the purchase by stationary source end users of any diesel fuel with a sulfur content exceeding 15 ppm on and after June 1, 2004.

AQMD Rule 1303 - New Source Review Requirements, which was last amended on December 6, 2002, requires BACT, modeling and emission offsets for any new or modified source which results in an emission increase of any nonattainment air contaminant, ozone depleting compound or ammonia.

AQMD Rule 1401 - New Source Review of Toxic Air Contaminants, which was last amended on May 2, 2003, specifies limits for maximum individual cancer risk (MICR), cancer burden, and non-cancer acute and chronic hazard index (HI) from new, modified and existing permitted sources which emit toxic air contaminants (TACs) listed in Table I of Rule 1401. Although numerous TACs may be emitted from engines, formaldehyde, acrolein, methanol, and acetaldehyde account for essentially all of the mass emissions. PAR 1110.2 target pollutants are NOx, VOC and CO.

AQMD Rule 1470 - Requirements for Stationary Diesel-Fueled Internal Combustion and Other Compression Ignition Engines, which was adopted on April 2, 2004, addresses primarily toxic diesel PM from new and existing, stationary, emergency and non-emergency, diesel engines, whereas Rule 1110.2 addresses only NOx, VOC and CO emissions.

AQMD Regulation XX - Regional Clean Air Incentive Market (RECLAIM) superceded many Regulation IV and Regulation XI rules for NOX and SOX for the largest facilities with an emission trading program that achieved equivalent emission reductions, but in a way to allow facilities flexibility in achieving emission reduction requirements for NOx and SOx by methods such as add-on controls, equipment modifications, reformulated products, operational changes, shutdowns, and the purchase of excess emission reductions. Facilities for which emission fee data for 1990 or subsequent year shows four or more tons per year of NOx or SOx, excluding certain exempt sources, are subject to this program. Regulation XX specifically identifies requirements for ICEs, in addition to other specific sources, which include monitoring, reporting and recordkeeping for NOx and SOx emissions.

DRAFT FINDINGS

Before adopting, amending or repealing a rule, the AQMD shall make findings of necessity, authority, clarity, consistency, non-duplication, and reference, as defined in Health and Safety Code Section 40727. The draft findings are as follows:

Necessity - The AQMD Governing Board finds and determines that Proposed Amended Rule 1110.2 - Emissions From Gaseous- and Liquid-Fueled Internal Combustion Engines is necessary in order to improve compliance and implement Best Available Retrofit Control Technology for inclusion in the State Implementation Plan.

Authority - The AQMD Governing Board obtains its authority to adopt, amend or repeal rules and regulations from Health and Safety Code §§40000, 40001, 40440, and 40720-40728.

Clarity - The AQMD Governing Board finds and determines that Proposed Amended Rule 1110.2 is written and displayed so that the meaning can be easily understood by persons directly affected by it.

Consistency – The AQMD Governing Board finds and determines that Proposed Amended Rule 1110.2 is in harmony with, and not in conflict with or contradictory to, existing statutes, court decisions, or federal or state regulations.

Non-Duplication – The AQMD Governing Board has determined that Proposed Amended Rule 1110.2 does not impose the same requirements as any existing state or federal regulations.

Reference - In adopting these proposed amendments and proposed rescinding, the AQMD Governing Board references the following statutes which AQMD hereby implements, interprets or makes specific: Health and Safety Code Sections 40001, and 40440.

REFERENCES

1. California Environmental Protection Agency - Air Resources Board “Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Spark-Ignited Internal Combustion Engines", November 2001.
2. South Coast Air Quality Management District, “Final Staff Report For Proposed Amendment of Rule 1110.2 - Emissions from Gaseous and Liquid-Fueled Engines” November 1997.
3. California Air Resources Board, “Staff Report: Initial Statement of Reasons for Proposed Rulemaking for Proposed Amendments to the Regulation for the Statewide Portable Equipment Registration Program”, February 26, 2004.
4. Compilation of Air Pollutant Emission Factors AP-42. Volume I: Stationary Point and Area Sources. U. S. Environmental Protection Agency, Research Triangle Park, NC.
5. California Air Resources Board, "Staff Report: Adoption of the Proposed Airborne Toxic Control Measure for Diesel Particulate Matter from Portable Engines Greater Than 50 Horsepower", February 26, 2004
6. South Coast Air Quality Management District, “Final Staff Report For Proposed Rule 1110.2 - Emissions from Gaseous and Liquid-Fueled Engines” July 1990
7. Environmental Technology Verification Report, Miratech Corporation GECO 3001 Air/Fuel Ratio Controller (Manufactured by Woodward Governor Company), by Southern Research Institute for USEPA, SRI/USEPA-GHG-VR-11, September 2001
8. McGivney, Daniel, Eastern Municipal Water District, “Evaluation of Potential Monitoring Frequency for Internal Combustion Engines Using Portable Electrochemical Cell Analyzers”, (Contractor: SCEC Air Experts), September 2006
9. Arney, Gregg, Southern California Gas Company, “Field Comparison of Air/Fuel Ratio Controllers for Detection of Excess Emissions from Rich-Burn Engines Equipped with Non-Selective Catalytic Reduction Systems”, (Contractor: Advanced Engine Technologies Corporation), September 22, 2006
10. Memorandum from Andrew Steckel of USEPA to Laki Tisopulos of AQMD dated March 31, 2005
11. “Critical Topics in Exhaust Aftertreatment”, Peter Eastwood, Ford Motor Company, Research Studies Press Ltd., Baldock, England, 2000
12. “Evaluation of Automotive Oxygen Sensors for Steady-State Air/Fuel Raio Control and its OBD Characteristics on Natural Gas Engines”, Jerry Cotrill, Miratech Corporation, 1999 Proceedings of the Spring Tech Conf ASME Ice-Modeling Simulation of Eng Processes Engine Emission: Volume 1
13. “Development of a 1.7 Liter CNG Engine for the 2001 Honda Civic GX”, Takushi Toda, et al, HONDA R AND D TECHNICAL REVIEW, 2002, VOL 14; PART 1, pages 49-56
14. “Evaluation of CO or THC Emissions Control Technology for Control of Organic Hazardous Pollutant Emissions from Natural Gas Fired Engines”, Colorado State University, GRI Report No. GRI-03/0107, August 2003

APPENDIX A

Stationary Engine Survey

To characterize the existing engine population affected by Rule 1110.2 in terms of important technical parameters, staff surveyed owners of stationary, non-emergency engines. This survey was conducted during the period February through May of 2005. Owners of engines subject to the rule were identified by a search of the AQMD permitting data base for all active permits and permits in process for stationary, non-emergency engines. This search identified 1304 stationary, non-emergency engines at 580 facilities. A survey form was sent to each facility with a request that the facility complete the form for each stationary, non-emergency engine rated over 50 hp. The following information was requested on the form.

Engine Size, hp
Engine Use: Generator. Pump, Compressor or Other
Emission Controls: Three-way catalyst with air/fuel ratio controller, Three-way catalyst without air/fuel ratio controller, Selective catalytic reduction (SCR), Pre-stratified charge combustion (PSC) or Combustion modifications
Engine Load: Variable, 100%, 90%, 80%, 70%, 60%, 50% or Unknown
Engine Efficiency, % (based on higher heating value)
Primary and Secondary Fuels: Natural Gas, Landfill Gas, Digester Gas, Field Gas, Gasoline, Propane, Diesel
Primary and Secondary Fuels Annual Usages
Emission Limits: NOx, CO, VOC
Date and Results of Most Recent Two Source Tests: NOx, CO, VOC

Of the 580 facilities that were contacted, 313 responded to the survey—a 54% facility response rate. In processing the information returned by the responding facilities, it was found that some of the stationary, non-emergency engines identified in the data base search do not exist. Reasons for non-existent engines included (1) the engine had been removed but the permit had not yet been cancelled, (2) the equipment designation in the data base ("BCAT" No.) was incorrect or (3) the same engine occurred twice in the data base because a permit modification was being processed and the active permit had not yet been cancelled. This left 907 stationary engines in the database.

Information was received for 631 stationary, non-emergency engines at 286 facilities, representing 70% of all permitted engines. The following tables and figures summarize the characteristics of this engine population.

Major Characteristics of the Engine Population

Table A-1 summarizes some major characteristics of the engine population for which survey information was received. Not surprisingly, a large majority of the engines use natural

Table A-1. Summary of Engine Survey Results

				Use, %				Type of NOx Limit, %		
Fuel	No. of Engines*	Rich-Burn, %	Lean-Burn, %	Generators	Pumps	Compressors	Other	BACT	Rule 1110.2	RECLAIM
Natural Gas (NG)	557	90	10	34	47	18	1	54	33	13
Digester Gas (DG)	25	0	100	72	0	20	8	12	88	0
Landfill Gas (LFG)	26	0	100	100	0	0	0	58	42	0
Diesel (D)	6	0	100	100	0	0	0	0	0	100
Field Gas (FG)	13	92	8	77	23	0	0	92	0	8
Digester Gas + Landfill Gas (DG/LFG)	3	0	100	100	0	0	0	0	100	0
Propane (P)	1	100	0	100	0	0	0	100	0	0
Total No. of Engines	631									

* The survey had a 70% response rate.

gas fuel although there are significant numbers fueled by waste gases—digester gas, landfill gas and oil field gas—and some are fueled by diesel.

Approximately 90% of the natural gas and field gas engines for which survey results were received are rich-burn engines while the engines fueled on digester and/or landfill gas, as well as the diesel engines, are lean-burn. The natural gas engines have the most diverse uses—driving pumps, generators, and compressors. The engines fueled on waste gases or diesel mostly drive generators although some of the digester gas engines drive compressors and some of the field gas engines drive pumps.

With regard to NOx limits, most of the natural gas engines for which survey information was received have modern BACT limits (i.e., 9-12 ppmvd @ 15% O2) although many are restricted only by the rule (36 to approximately 60 ppmvd NOx @ 15% O2) and some are in RECLAIM. Most of those that are in RECLAIM have NOx limits much higher than the rule would allow, however some have taken concentration limits that are comparable to what the rule would allow or even to modern BACT. None of the engines fueled on waste gases are in RECLAIM, and these engines are about equally divided between being governed by the rule and having modern BACT limits. The six diesel engines are all in RECLAIM.

Information was received for one propane fueled engine, which is a rich-burn engine with modern BACT limits and drives a generator.

Rule 1110.2 allows, for most engines, higher NOx and VOC limits for an engine with efficiency greater than 25% (HHV). Table A-2 shows, for each fuel, the number and percent of engines for which survey information was received that are non-RECLAIM and taking advantage of the efficiency correction. The natural gas engines using the efficiency factor are all rich-burn, non-RECLAIM engines.

Table A-2. Non-RECLAIM Engines Using Efficiency Correction Allowed in Rule

Fuel	No.	%
NG	89	16.0
DG	13	52.0
LFG	3	11.5
FG	0	0.0
DG/LFG	3	100.0
Prop.	0	0.0
Total	108	17.1

Table A-3 shows the number and percent of engines for which survey information was received using various types of emission controls, again broken down by fuel. Table A-4 shows, for all engines for which efficiency was reported, the average efficiency for each fuel and engine type—rich- or lean-burn.

Table A-3. Emission Controls

Fuel	Three-Way Catalyst with Air/Fuel Ratio Controller		Three-Way Catalyst without Air/Fuel Ratio Controller		Selective Catalytic Reduction		Pre-Stratified Charge		Combustion Modifications		Other or Unspecified	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
NG	467	83.8	12	2.2	19	3.4	6	1.1	26	4.7	27	4.8
DG							10	40.0			15	60.0
LFG							2	7.7	18	69.2	6	23.1
Diesel					6	100.0						
FG	12	92.3									1	7.7
DG/LFG											3	100.0
Propane	1	100.0										
Total	480	76.1	15	1.9	25	4.0	18	2.9	45	7.1	52	8.2

Table A-4. Average Efficiency (Based on Higher Heating Value of Fuel), %

NG	30.8	32.5
DG		30.9
LFG		31.2
Diesel		33.5
FG	26.7	40.0
DG/LFG		32.5
Propane	32.5	
Avg.	30.0	33.4

Calculated TPY Emissions

Table A-5 shows calculated tons-per-year (TPY) emissions from engines at facilities that responded to the survey, with the results broken down by engine category in terms of fuel and rich- or lean-burn. These figures were calculated based on fuel consumption data provided by the engine owners and emission factors derived from permit limits and source test data. The NOx emission factors for engines in RECLAIM were equated to those being used in RECLAIM, and for non-RECLAIM engines were based on the NOx limits in the permits. The NOx emissions from RECLAIM major sources are based on actual CEMS data. The CO and VOC emission factors were based on the permit limits for BACT engines and for non-BACT engines were based on source test data. These assumptions result in emission estimates that are somewhat more realistic than using only source test data, but these estimates do assume that engines comply with their emission limits, which known to not always be the case.

Table A-5. Emissions (Based on Reported Annual Fuel Usage), TPY

	Rich-Burn			Lean-Burn			All Reported Engines		
	NOx	CO	VOC	NOx	CO	VOC	NOx	CO	VOC
NG	224	1,090	123	121	273	65	346	1,363	188
DG				167	606	74	167	606	74
LFG				187	637	44	187	637	44
Diesel				107	129	47	107	129	47
FG	18	71	18	4	1	0	21	72	18
DG/LFG				7	34	2	7	34	2
Prop.	0	0	0						
Total	242	1,161	141	593	1,679	232	835	2,840	373
Scaled TPY	348	1,668	202	851	2,413	334	1,199	4,080	535
Scaled TPD	0.95	4.57	0.55	2.33	6.61	0.91	3.29	11.18	1.47

*Calculation basis:
NOx - permit limit, RECLAIM emission factor, or RECLAIM actual
CO and VOC - source test data or BACT limits
For engine with no source test data, used category average (by fuel, rich/lean, BACT/non-BACT).
Survey had a 70% response rate. TPY figures reflect engines for which responses were received.

Scaling up the 70% response rate to a 100% response rate, the estimated total annual tonnage emissions from all permitted stationary, non-emergency IC engines are 1,199 TPY NOx, 4,080 TPY CO and 536 TPY VOC (3.29 TPD NOx, 11.2 TPD CO and 1.47 TPD VOC). The 54 engines fueled on landfill and/or digester gas, representing only 8.5% of the engines in the survey, account for 42% of the NOx emissions, 44% of the CO emissions and 24% of the VOC emissions. The six diesel engines in the survey, which are large RECLAIM major sources engines operated by Southern California Edison Company on Catalina Island, represent less than 1% of the engines in the survey but produce 13% of the NOx emissions. Rich-burn and lean-burn natural gas engines are the second and third highest emitters of all three pollutants.

However, actual emissions from rich-burn engines are known to be significantly higher than these calculated estimates for that category because of frequent and substantial excursions above permit limits. Lean-burn engines emissions may also be somewhat higher.

Compliance with Rule 1110.2 Source Testing Requirement

Rule 1110.2 requires that a source test be performed every three years. The survey requested the two most recent source tests. A substantial number of engines appeared to be probably delinquent in this regard. Engines that had, based on the date of application for Permit to Construct, probably been operating for at least three years and had not been source tested within the past three years or had probably been operating for at least six years and had not been source tested twice within the most recent six years were considered to be delinquent. Probable delinquent engines numbered 213, which is 33.8% of the engines for which information was received. The delinquency rate may be higher among those engines for which information was not received.

Size Characteristics of the Engine Population

Figures A-1 to A-3 show the size characteristics of the engines for which survey responses were received. Overall, the engines range in size from 61 to 5500 hp, and the median size is approximately 400 hp. The rich-burn engines range in size from 61 to 2200 hp with a median size of about 250 hp, and the lean-burn engines range from 88 to 5500 hp with a median size of about 1900 hp. These statistics may be biased toward larger engines since facilities with larger engines were probably more likely to respond to the survey.

Figure A-1. Engine Distribution versus Size, All Engines

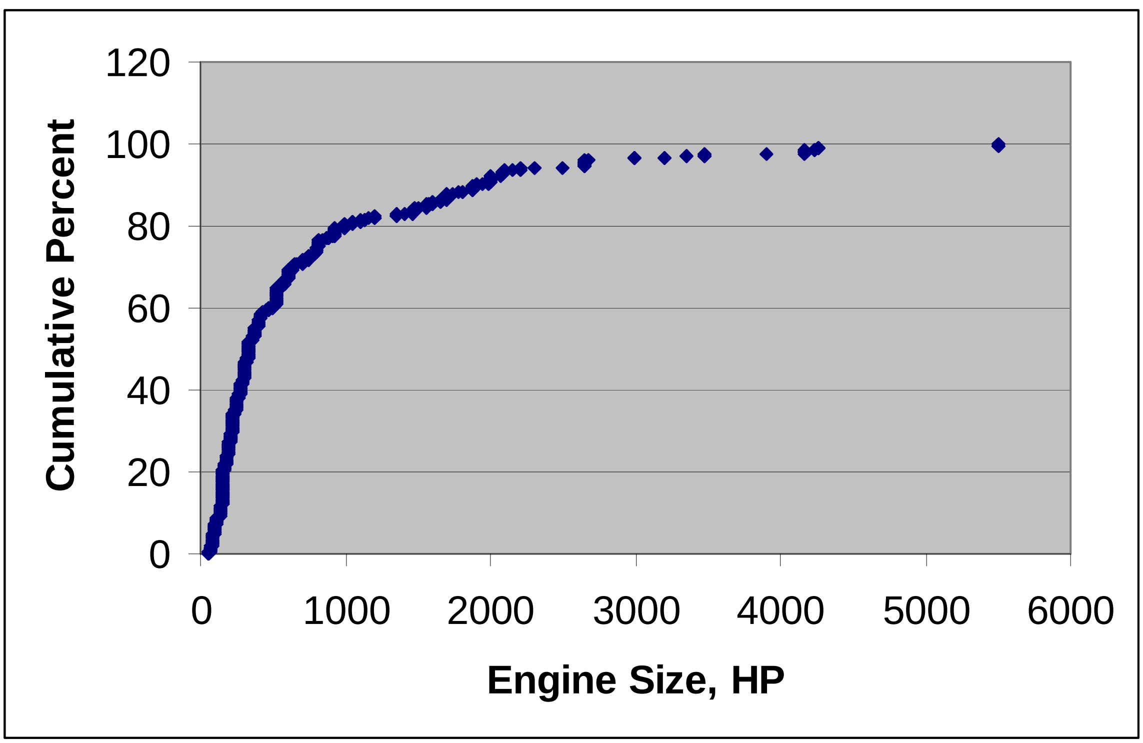


Figure A-2. Engine Distribution versus Size, Rich-Burn Engines

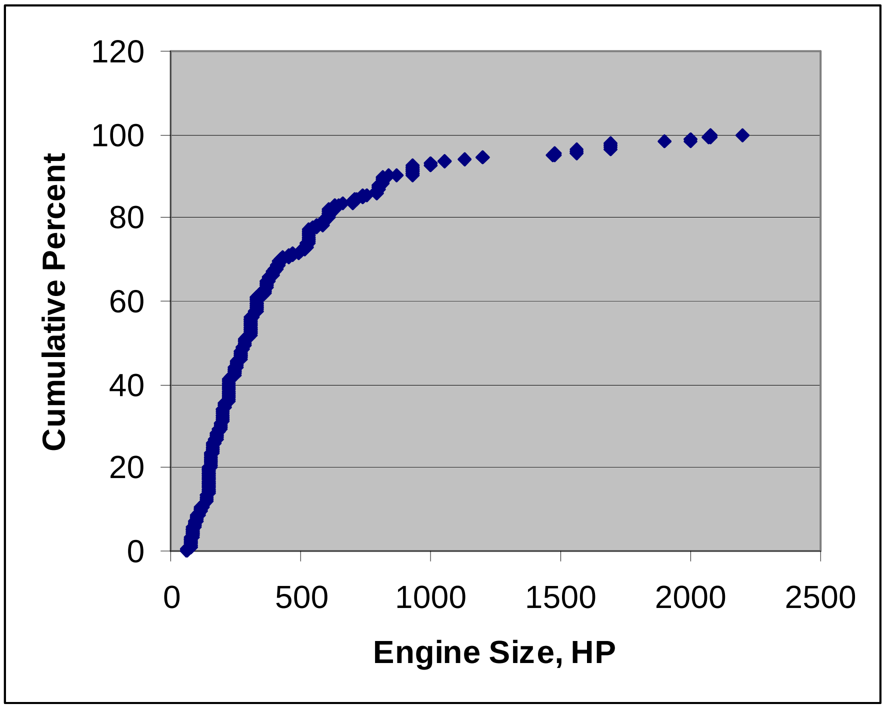
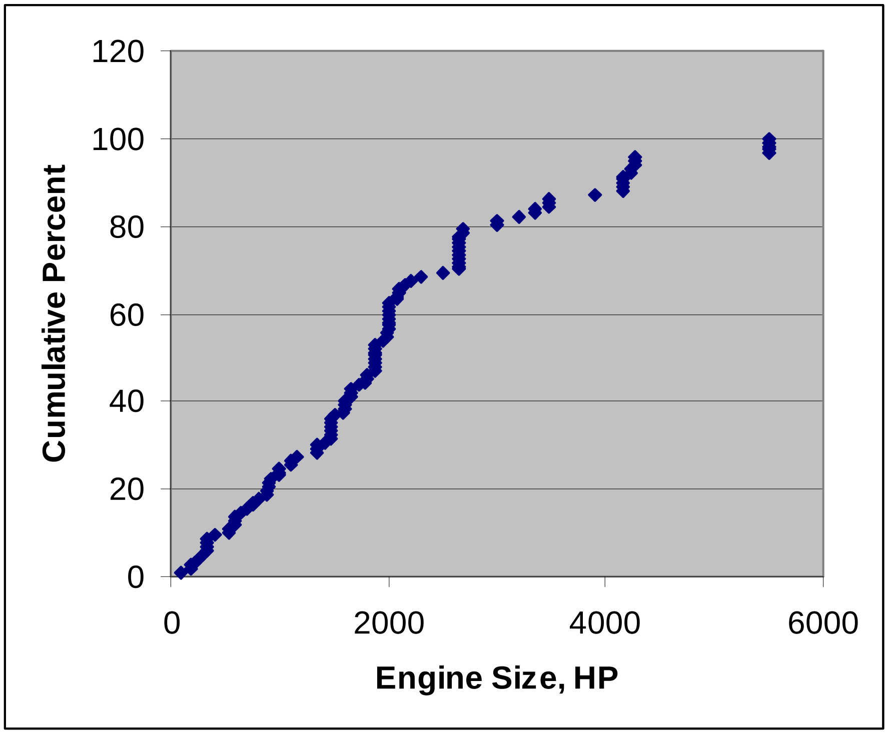


Figure A-3. Engine Distribution versus Size, Lean-Burn Engines



Number of Engines and Total Horsepower at the Facility

Table A-6 shows the number of facilities having various engine counts. The maximum number of stationary, non-emergency engines at any one facility among those responding to the survey was ten (10). A large majority, 245, of the facilities have one, two or three engines. Twenty-nine (29) of the facilities have four, five or six engines, and 12 facilities have more than six engines. These statistics may be biased toward facilities with higher engine counts since larger facilities were probably more likely to respond to the survey.

Table A-6. Number of Engines at Facility

Number of Engines at Facility	Number of Facilities
1	148
2	49
3	48
4	12
5	10
6	7
7	3
8	3
9	4
10	2
Total Facilities	286

Figure A-4 shows the total stationary, non-emergency engine horsepower of the responding facilities. A majority, 65.7 %, have 1000 hp or less, i.e., 34.3 % of the facilities have more than 1000 total horsepower. The number of facilities with larger total horsepower diminishes rapidly—26.2 % have more than 1500, 16.4 % have more than 2000 and 7.7 % have more than 5000. Again, these statistics may be biased toward facilities with larger total horsepower since larger facilities were probably more likely to respond to the survey.

Figure A-5 shows total facility horsepower sorted by number of engines at the facility.

Figure A-4. Total Facility Horsepower

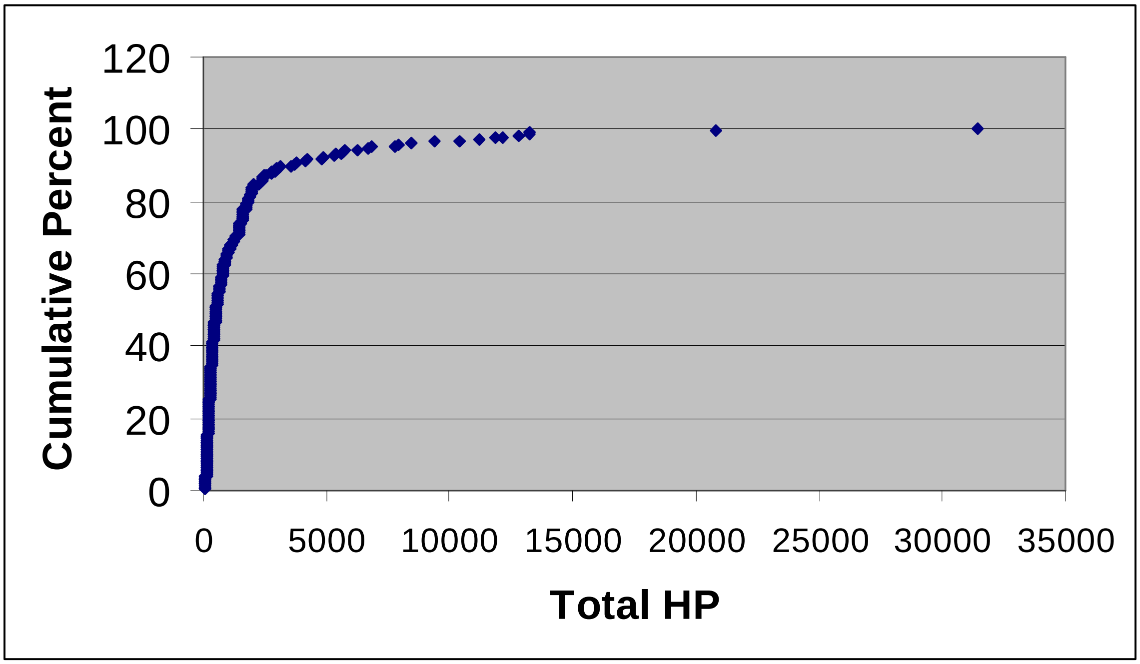
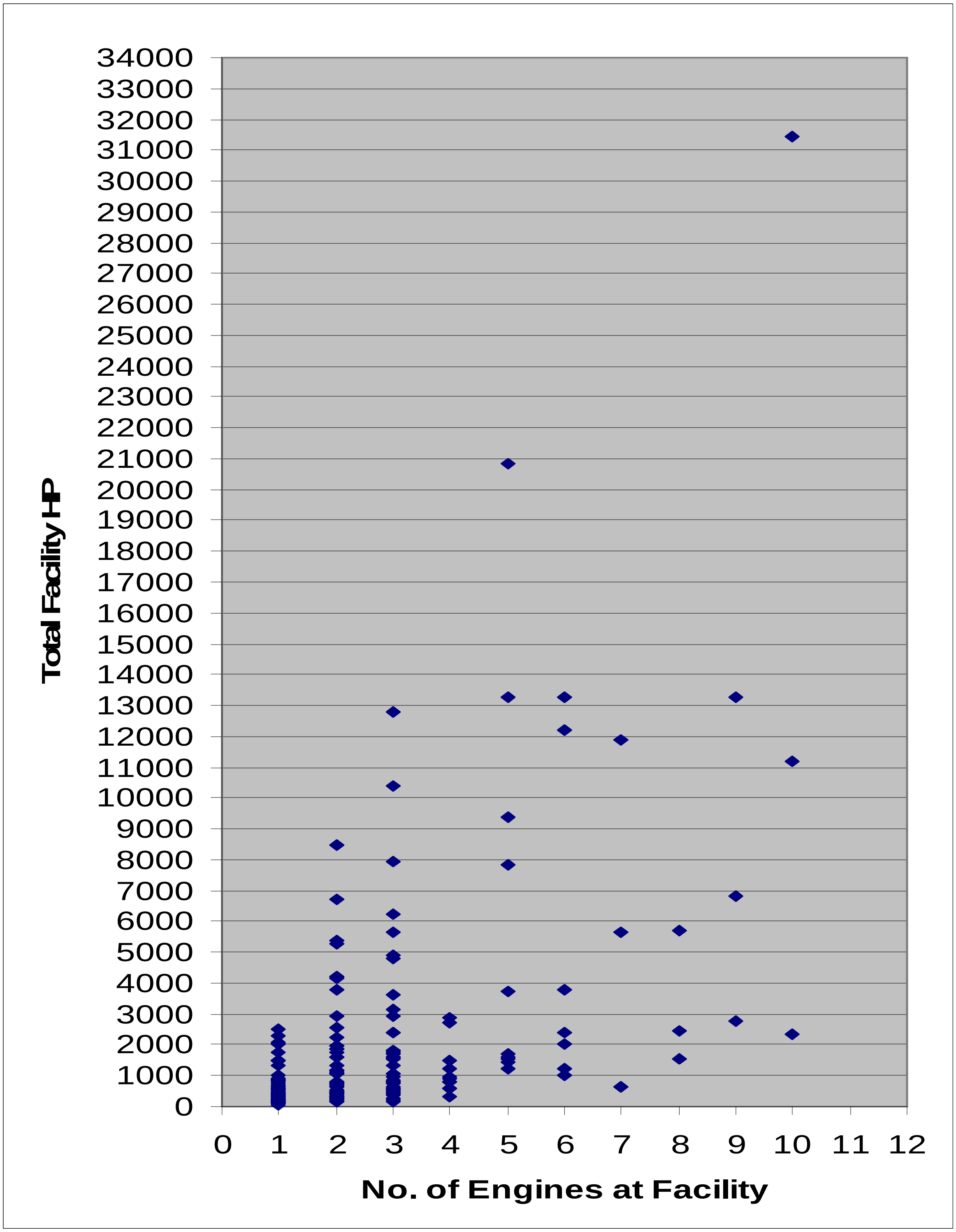


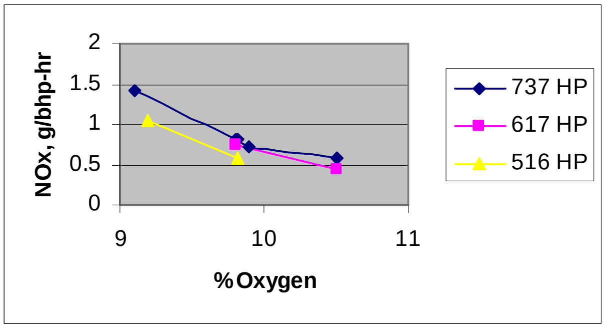
Figure A-5. Number of Engines at Facility and Total Facility Horsepower

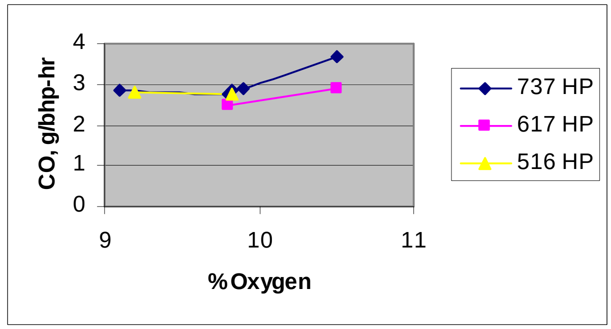


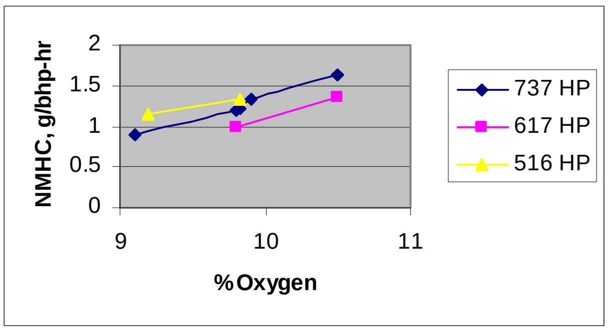
APPENDIX B

Effects of Exhaust O_2 Concentration on Lean-Burn Engines

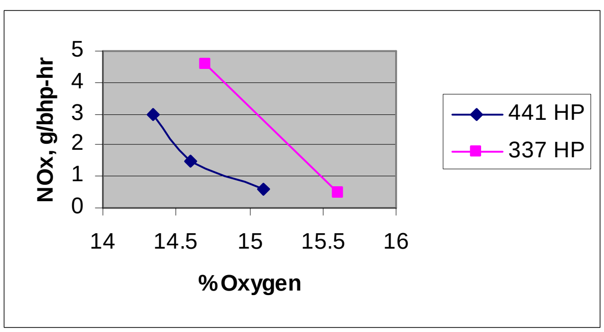
Reference: EPA-454/R-00-037: Testing of a 4-Stroke Lean Burn Gas-fired Reciprocating Internal Combustion Engine to Determine the Effectiveness of an Oxidation Reduction Catalyst System for Reduction of Hazardous Air Pollutant Emissions, September 2001

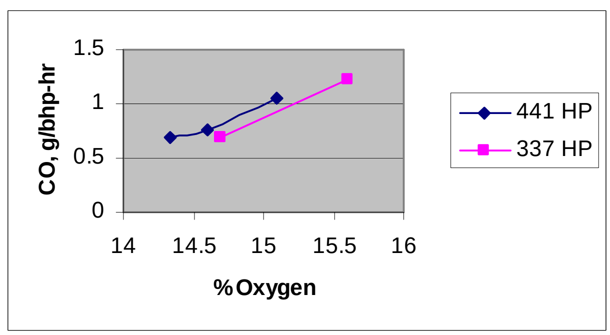


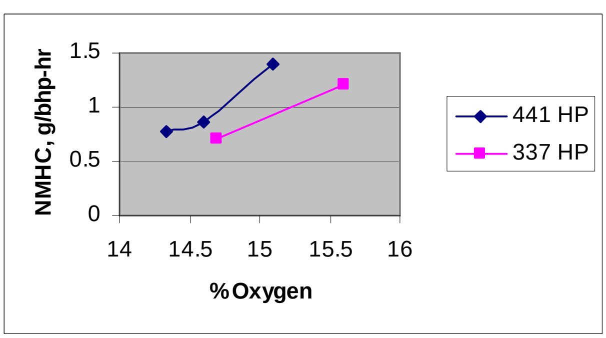




Reference: EPA-454/R-00-036a: Testing of a 2-Stroke Lean Burn Gas-fired Reciprocating Internal Combustion Engine to Determine the Effectiveness of an Oxidation Reduction Catalyst System for Reduction of Hazardous Air Pollutant Emissions, July 2000







Note: The emissions in these graphs are from the engine, before the oxidation catalyst.

APPENDIX C

Rich-Burn Engine Oxygen Sensor Set Points Drift

This appendix provides information demonstrating the problem of oxygen (O2) sensor drift. The data were obtained with the cooperation of Tecogen, Inc., a manufacturer of small rich-burn engine-based combined heat and power systems.

Tecogen has developed its own air-to-fuel ratio controller (AFRC) for their rich-burn engines. As with other AFRCs, it uses an oxygen sensor upstream of the catalyst to maintain a constant air-to-fuel ratio (AFR). These data were obtained when Tecogen used only a upstream O2 sensor. More recently they have begun using upstream and downstream O2 sensors.

The O2 sensor (also called a Lambda sensor) has a non-linear, and temperature-dependant output from 0 to 1000 millivolts (mV). As the AFR increases (i.e. becomes more lean) the mV output of the O2 sensor declines.

AFRCs for rich-burn engines with three-way catalysts (TWC) usually try to maintain the AFR at slightly rich of stoichiometric, which means the equivalence ratio (ER) is a slightly more than 1.0[23]. The window for proper operation of the TWC may be as little as 0.5% of the AFR, or an ER window of 0.005. Because the engine exhaust temperature varies with load, and the O2 sensor output varies with temperature, the proper O2 sensor set point may vary at different loads.

When a new O2 sensor is installed, a Tecogen service technician normally uses a portable emission analyzer (NOx, CO and O2) to determine the proper set points for the AFRC. The technician determines set points for 75 kW (full-load) and 35 kW. The AFRC interpolates for other loads in between these. In this particular case, the technician also determined at three different loads, 35 kW, 50 kW and 75 kW, the maximum and minimum O2 sensor mV outputs within which the engine could remain in compliance with its emission limits (11 ppm NOx and 72 ppm CO, dry and corrected to 15% O2). The CO emission limit determines the upper mV limit and the NOx emission limit determines the lower mV limit. The technician did this three times during the life of this particular O2 sensor: when it was new; at 667 operating hours; and at 1357 operating hours. O2 sensors last about 2000 hours.

Figure C-1 shows the three different pairs of set points determined during the life of the O2 sensor. As the sensor aged, the set points had to be manually adjusted upward to keep the TWC within the proper window of AFR for emissions compliance.

With the new sensor, the set points at both loads were the same, 604 mV. Figure C-2 shows the new set points and upper and lower O2 sensor limits that were established after 667 hours of operation and compares them to the set points that were in effect until the readjustment. Because of the upward drift in the O2 sensor signals, the original set points were no longer within the range necessary to keep the engine emissions in compliance.

The O2 sensor set points were re-established again at 1357 hours, and as shown by Figure C-3, the previous set points established at 667 hours were again no longer within the range necessary to keep the engine emissions in compliance.

[23] Equivalence ratio (Φ) is the actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. The Lambda value (λ) is the reciprocal of Φ.

Figure C-1 - Unit 1 O2 Sensor Setpoints Drift

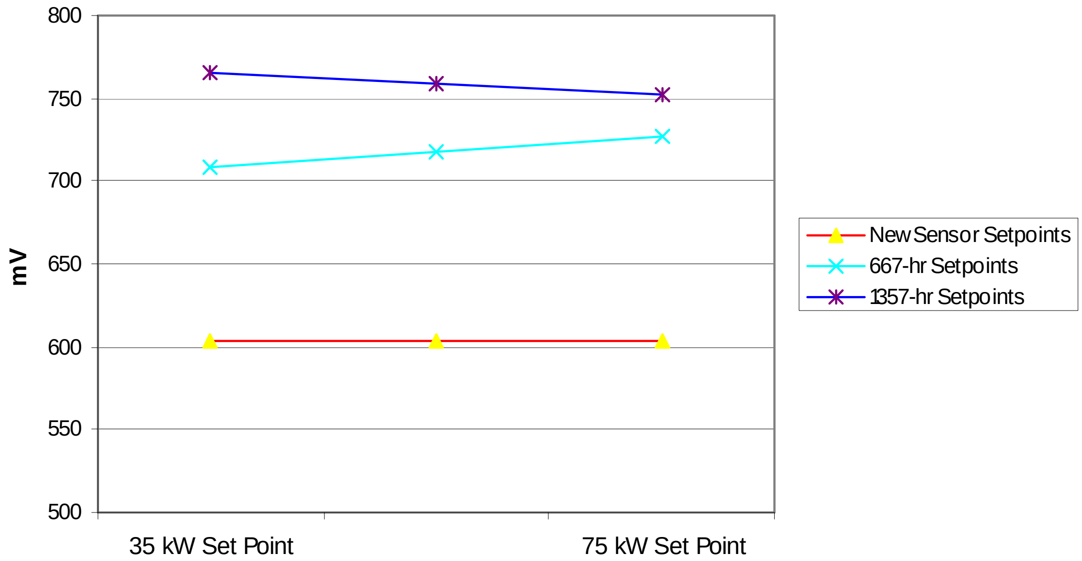


Figure C-2 - Unit 1 667-hr O2 Sensor Setpoints and Compliance Limits Compared to New Sensor Setpoints

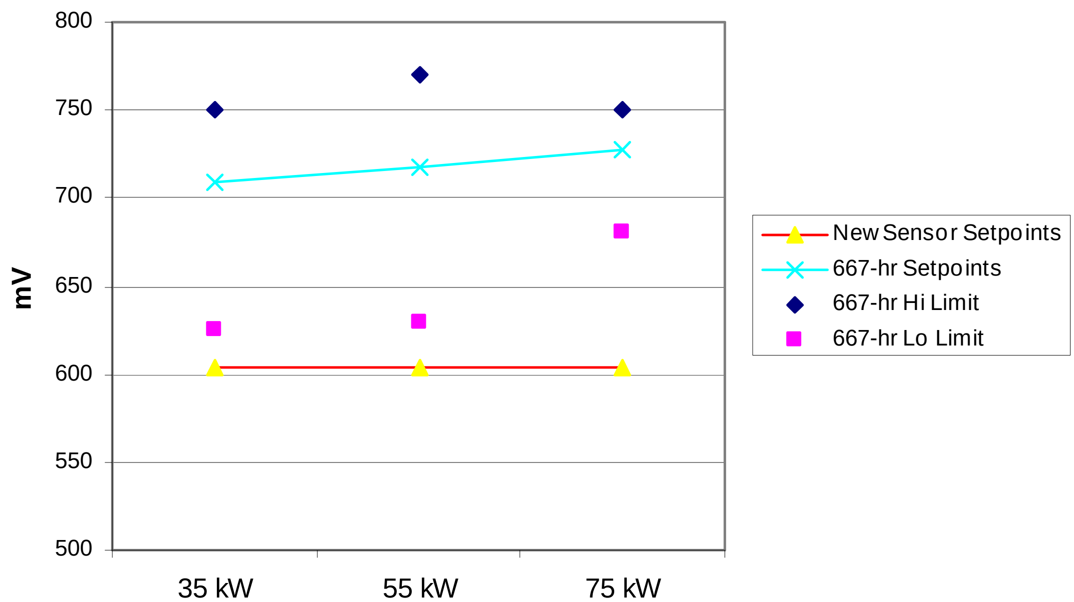
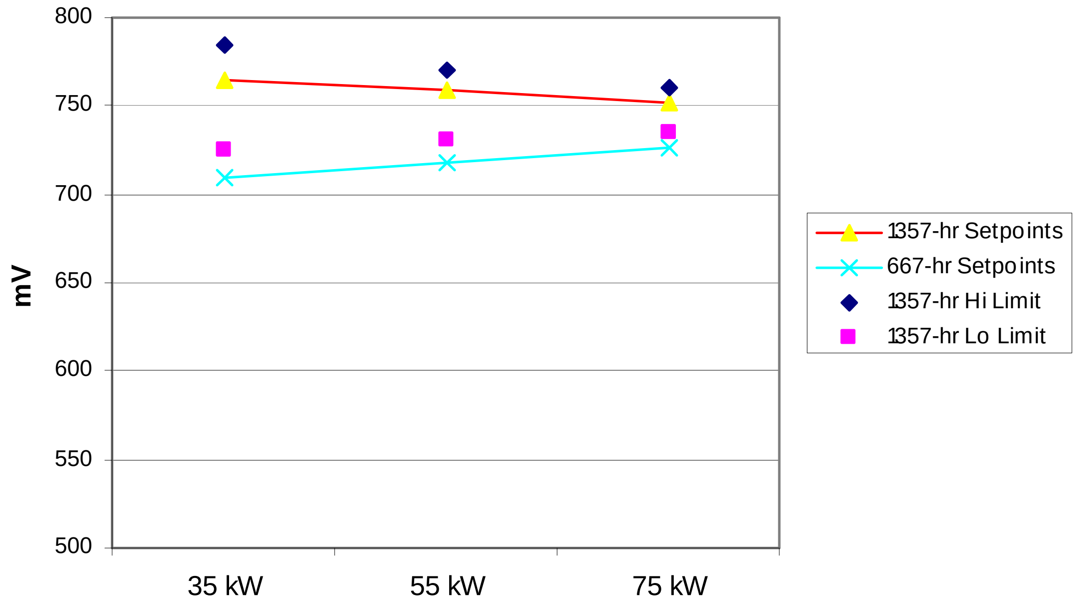


Figure C-3 - Unit 1 1357-hr O2 Sensor Setpoints and Compliance Limits Compared to 667-hr Setpoints



APPENDIX D

DESCRIPTION OF SPARK-IGNITED IC ENGINES AND IC ENGINE CONTROLS

(The information is in this Appendix is from Appendix B of Reference 7, “Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Spark-Ignited Internal Combustion Engines" by CARB, November 2001)

I. DESCRIPTION OF SPARK-IGNITED IC ENGINES

The main parts of a piston-type (also known as reciprocating) spark-ignited (SI) internal combustion (IC) engine include pistons, combustion chambers, a crankshaft, and valves or ports. IC engines generate power from the combustion of an air/fuel mixture. The combusted mixture drives the piston, which is connected by a rod to the crankshaft, so that the back-and-forth motion of the piston is converted into rotational energy at the crankshaft. This rotational energy drives power equipment such as pumps, compressors, or electrical generators.

There are several key aspects of engine design and operation that influence emissions and emissions control. These include the basic design of the engine, the manner in which combustion is initiated, the type of fuel used, the introduction of intake air, the air/fuel ratio, and the operational mode of the engine. A brief description of these aspects is given below.

A. Basic Engine Design

Piston-type internal combustion engines are generally classified as either four or two stroke. Four operations occur in all piston-type internal combustion engines: intake, compression,power, and exhaust. Four stroke engines require two revolutions of the crankshaft to complete all four operations, while two stroke engines require only one revolution.

In four stroke engines, a single operation is associated with each movement of the piston. During the intake stroke, the intake valve opens, and gas is drawn into the combustion chamber and cylinder by the downward motion of the piston. In carbureted and indirect fuel injected engines, fuel is mixed with air before being introduced into the combustion chamber, and thus the gas drawn into the combustion chamber is an air/fuel mixture. In direct gas injection engines, the fuel is injected into the combustion chamber while air is drawn in by the downward motion of the piston. At or shortly after the end of this downward movement, the valves close and the compression stroke begins with the pistons moving upward, compressing the air/fuel mixture. A spark plug ignites the air/fuel mixture. During the power stroke, the hot, high-pressure gases from combustion push the pistons downward. The exhaust stroke begins when the piston nears its full downward position. At that point, the exhaust valves open, and the piston reverses its motion, moving upward to push the exhaust gases out of the combustion chamber. Near the full upward travel of the pistons, the exhaust valves close, the intake valves open, and the intake stroke is repeated.

In a two stroke engine, instead of intake valves, there are one or more ports (i.e., openings) in each cylinder wall that are uncovered as the piston nears its full downward movement. Two stroke engines use either exhaust valves similar to four stroke engines, or exhaust ports located in each cylinder wall across from the intake ports. When the pistons reach their full downward travel, both the intake ports and the exhaust ports or valves are open, and the exhaust gases are swept out by the air/fuel mixture that is transferred into the cylinder through the intake ports. In order to effect this transfer, the intake air must be pressurized. This operation is often referred to as scavenging. The pressurization can result from introducing the air into a sealed crankcase. An air/fuel mixture is pulled into the sealed crankcase through the upward movement of the piston, and is pressurized by the downward movement of the piston. Alternatively, a supercharger or turbocharger can be used to compress the intake air. The compression and power strokes for a two-stroke engine are similar to those for a four-stroke engine.

B. Combustion Initiation

In SI engines, (also called Otto cycle), the fuel is usually mixed with intake air before introduction into the combustion chamber, resulting in a relatively homogeneous air/fuel mixture in the combustion chamber. Once the spark plug initiates combustion, the homogeneous mixture propagates the flame throughout the combustion chamber during the power stroke.

C. Type of Fuel

SI engines can use natural gas, landfill gas, digester gas, field gas, refinery gas, propane,

methanol, ethanol, gasoline, or a mixture of these fuels. Natural gas consists almost exclusively of methane. Field gas refers to the raw gas produced from oil or gas production fields and contains varying amounts of hydrogen sulfide which can clog exhaust catalysts and render them ineffective in controlling NOx. Refinery gas refers to the gas generated by oil refinery processing. Field gas and refinery gas consist of mostly methane, but contain more of the heavier gaseous hydrocarbon compounds than natural gas. Landfill gas is generated from the decomposition of waste materials deposited in landfills. Landfill gas can vary from 25 to 60 percent methane, with the remainder being mostly inert gases such as carbon dioxide and nitrogen. Digester gas is generated from the anaerobic digestion of solids at sewage treatment plants. Digester gas is typically about two-thirds methane, while the remaining one-third is mostly inert gases such as carbon dioxide.

Significant amounts of gaseous sulfur compounds may also be present in landfill and digester gas. The sulfur content of the fuel is important, as exhaust catalysts may be adversely affected by high levels of sulfur. In addition, waste gases may contain methylated siloxanes which could poison or mask exhaust catalysts.

D. Introduction of Intake Air

On many engines, the intake air is compressed by a supercharger or turbocharger before it enters the combustion chamber. This compression can increase engine power substantially. The major parts of a turbocharger consist of a turbine and compressor. Exhaust gases from the combustion chamber which are under high temperature and pressure pass through the exhaust pipe into the turbine, causing the turbine blades to spin. The turbine is connected by a shaft to a compressor. Intake air is directed into the compressor, where it is pressurized before passing through the intake manifold into the combustion chamber. The turbocharger allows the engine to pass a greater mass of air through the combustion chamber, which allows more fuel to be added and more power to be produced. Turbocharging also improves the overall efficiency of an engine.

Superchargers work in a similar fashion to turbochargers, except a mechanical power drive off the engine rather than exhaust gas powers the compressor. Less power is required to run a turbocharger than a comparable supercharger, and therefore turbocharged engines tend to be slightly more efficient than supercharged engines.

Engines not equipped with turbochargers or superchargers are referred to as naturally aspirated. Two stroke engines sometimes use superchargers to displace exhaust with intake air, but this design generally does not result in any significant pressurization of the intake air, and such engines are also classified as naturally aspirated.

E. Air/Fuel Ratio

Another basic engine parameter is the air/fuel ratio. Stoichiometry is defined as the precise air-to-fuel ratio where sufficient oxygen is supplied to completely combust fuel. A stoichiometric air/fuel ratio provides exactly enough oxygen to fully atomize the fuel for complete combustion. Rich of stoichiometry refers to fuel-rich combustion, i.e., operation at any air-to-fuel ratio less than stoichiometry. Lean of stoichiometry refers to fuel-lean combustion, i.e., operation at any air-to-fuel ratio numerically higher than stoichiometry.

Two-stroke, spark-ignited engines are lean-burn, while naturally aspirated, four-stroke SI engines are generally rich-burn. Turbocharged, spark-ignited engines can be either rich-burn or lean-burn, depending on design. Lean-burn engines tend to be more efficient but larger in size and higher in capital cost than rich-burn engines of the same power output. Also, smaller engines tend to be rich-burn, while larger engines tend to be lean-burn.

SI engines exhibit peak thermal efficiency (and also peak NOx emissions) at an air/fuel ratio that is about 6 to 12 percent leaner than stoichiometric. Efficiency (and NOx emissions) decrease if the mixture becomes leaner or richer than this peak efficiency ratio (see Figure B-1).

If the mixture is enriched, NOx emissions can be reduced to about 50 percent of their peak value before encountering problems with excessive emissions of CO, VOC, and possibly smoke. If the mixture is leaned from the peak efficiency air/fuel ratio, significant NOx reductions are possible.

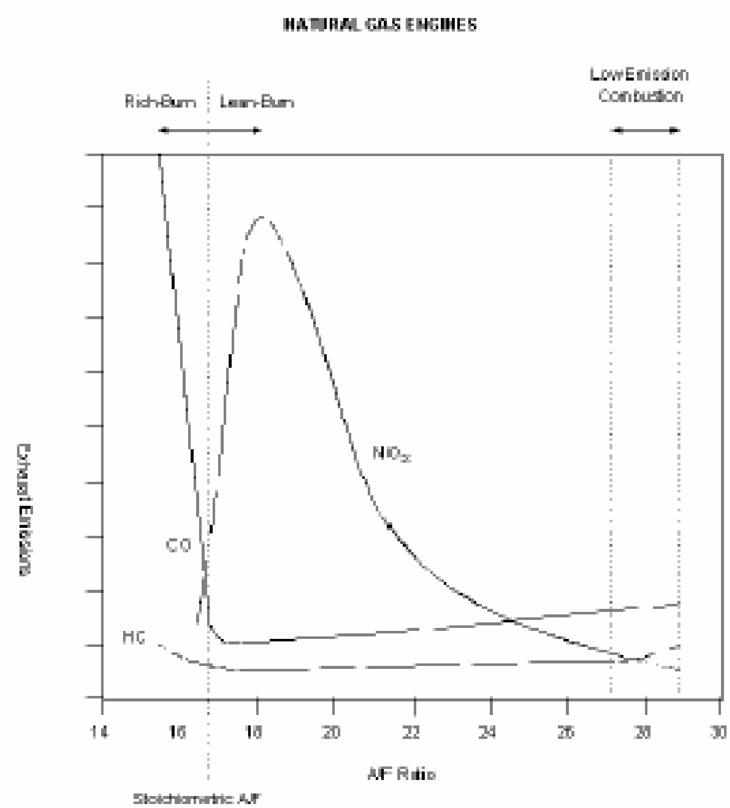


Figure B-1: The Effect of Air-to-Fuel Ratio on NOx, CO, and HC Emissions (Provided by GRI)

As the mixture is leaned, at some point the engine will have difficulty in initiating combustion of the lean air/fuel mixture. One of the more popular methods of overcoming ignition difficulties with lean mixtures is to incorporate precombustion chambers into the engine head. A precombustion chamber is a small combustion chamber which contains the spark plug. A rich mixture is introduced into the precombustion chamber, which is ignited by the spark plug. Passageways from the precombustion chamber to the main combustion chamber allow the flame front to pass into and ignite the lean mixture in the main combustion chamber. Precombustion chambers used alone or in combination with other NOx reduction technologies are known as low-emission combustion. This approach is described in more detail later in this appendix.

Another method used to assist combustion of lean mixtures (especially in smaller engines) is to redesign the intake manifold and combustion chamber to promote more thorough mixing, so that a more uniform air/fuel mixture is present in the combustion chamber. A third method is to use an improved ignition system that sparks either more frequently or continuously.

F. Operational Mode

Reciprocating IC engines can be used in several operational modes. In many cases, they are used continuously under a constant power load, shutting down only when there is a breakdown, or when maintenance or repair work is required. Other engines operate cyclically, changing their power output on a regular, frequent schedule. One of the more common cyclic applications is an oil well pump, where an engine may operate at load for a time period varying from several seconds to about 20 seconds, followed by an equal amount of time operating at idle.

Some engines may operate continuously, but for only part of the year. In many cases, this intermittent operation is seasonal. In other cases, engines are portable, and are used only for a specific, short-term need. In still other cases, engines are used infrequently, for emergency purposes. Such engines may operate for no more than a few hours per year during an emergency, and are also tested routinely, typically for less than an hour once a week. Other engines may operate in modes that combine the characteristics of cyclic and continuous operations.

The operational mode of the engine is an important consideration when adopting control regulations. The operational mode may impact operating parameters such as exhaust gas temperature, which often must be taken into account when designing and applying controls. The operational mode may also affect the impact of emissions on air quality. For instance, an engine that operates only during summer, which is the peak ozone season, will have a much greater impact on ambient air quality violations than an engine with the same annual emissions that operates year round.

II. DESCRIPTION OF IC ENGINE CONTROLS

Combustion of fossil fuels results in emissions of criteria pollutants and their precursors (i.e., NOx, CO, particulate matter, VOC, and sulfur oxides (SOx)). Controls for one pollutant sometimes increases the emissions of one or more other pollutants. If this occurs, controls can often be used for these other pollutants which will fully mitigate the increase. SOx is generally controlled by limiting the sulfur content of the fuel and is not discussed further in this determination, except as it affects emissions of other pollutants.

The following discussion of controls emphasizes the control of NOx. NOx emissions from stationary engines are generally far greater than for the other four pollutants.

NOx is generated in internal combustion engines almost exclusively from the oxidation of nitrogen in the air (thermal NOx) and from the oxidation of fuel-bound nitrogen (fuel NOx). The generation of fuel NOx varies with the nitrogen content of the fuel and the air/fuel ratio. The generation of thermal NOx varies with the air/fuel ratio, flame temperature, and residence time. Most fuels used in IC engines have relatively low fuel-bound nitrogen, so the principal NOx generation mechanism is thermal NOx. Even in cases where a high nitrogen content fuel such as crude oil or residual fuel oil is used, thermal NOx generation is generally far greater than fuel NOx generation due to the high combustion temperatures present.

There are probably more different types of controls available to reduce NOx from IC engines than for any other type of NOx source. These controls can be placed into one of four general categories: combustion modifications, fuel switching, post combustion controls, and replacement with a low emissions engine or electric motor. These controls are discussed in the following sections.

A. Combustion Modifications

Combustion modifications can reduce NOx formation by using techniques that change the air/fuel mixture, reduce peak temperatures, or shorten the residence time at high temperatures. The most frequently used combustion modifications include retarding the ignition, leaning the air/fuel ratio, adding a turbocharger and aftercooler, and adding exhaust gas recirculation.

Emissions of CO, particulate matter, and VOC are generally the result of incomplete combustion. They can be controlled by combustion modifications that increase oxygen, temperature, residence time at high temperatures, and the mixing of air and fuel. Note, however, that many of these modifications tend to increase NOx emissions. Care must be taken when applying these modifications to assure that reductions in one pollutant do not result in an unacceptable increase in other pollutants. These pollutants can also be controlled by post combustion controls such as oxidation catalysts and particulate traps.

1. Ignition Timing Retard

Applicability: This technique can be used on all spark-ignited (SI) engines. The technique has been widely used on motor vehicle engines, but is less popular on stationary source engines.

Principle: The ignition is retarded in SI engines by delaying the electrical pulse to the spark plug. As a result, the spark plug fires later, resulting in more of the combustion taking place as the piston begins its downward movement. This reduces both the magnitude and duration of peak temperatures.

Typical Effectiveness: NOx reductions for ignition timing retard are approximately 15 to 30 percent.

Limitations: SI engines are more sensitive than CI engines to operational problems associated with timing retard, and SI engines with excessive retard tend to misfire and exhibit poor transient performance. NOx reductions can be achieved with this technique, but there are limitations. Ignition timing should be retarded per the engine manufacturer's specifications and recommendations in order to avoid problems during engine operation.

Other Effects: Ignition timing retard will result in greater fuel consumption and higher exhaust temperatures, which could cause excessive exhaust valve wear. The maximum power output of the engine is also reduced, but this reduction is generally minor. Ignition timing retard will also result in greater emissions of VOC and HAPs.

Costs: This method has relatively low capital and operating costs. The cost of adjusting timing to retard the ignition should be less than $300.

2. Air/Fuel Ratio Changes

Applicability: This technique can be used on all SI engines, and has been used extensively on a wide variety of engines.

Principle: NOx formation is a strong function of the air/fuel ratio as shown in Figure B-1. Emissions of CO and VOC are also strong functions of the air/fuel ratio. Stoichiometry is achieved when the air/fuel ratio is such that all the fuel can be fully oxidized with no residual oxygen remaining. NOx formation is highest when the air/fuel ratio is slightly on the lean side of stoichiometric. At this point, both CO and VOC are relatively low. Adjusting the air/fuel ratio toward either leaner or richer mixtures from the peak NOx formation air/fuel ratio will reduce NOx formation. In the case of leaner mixtures, the excess air acts as a heat sink, reducing peak temperatures, which results in reduced NOx formation. The excess air also allows more oxygen to come into contact with the fuel, which promotes complete combustion and reduces VOC and CO emissions. As the mixture continues to be leaned out, the reduced temperatures may result in a slight increase in CO and VOC emissions. For extremely lean mixtures, misfiring will occur, which increases VOC emissions dramatically.

Operating the engine on the lean side of the NOx formation peak is often preferred over operating rich because of increased fuel efficiencies associated with lean operation. When adjusting the air/fuel ratio, once an engine is leaned beyond the peak NOx air/fuel ratio, there is approximately a 5 percent decrease in NOx for a 1 percent increase in intake air. However, this rate of decrease in NOx becomes smaller as the mixture becomes leaner. Leaning the mixture beyond the optimal air/fuel ratio associated with peak fuel efficiency will result in increased fuel consumption. Compared to the most efficient air/fuel ratio, there is a fuel consumption penalty of about 3 percent when an engine is leaned sufficiently to reduce NOx by 50 percent. Fuel consumption increases exponentially if the mixture is leaned further.

NOx formation will also decrease if the mixture is richened from the peak NOx air/fuel ratio. However, the effect on NOx is generally not as great as that associated with leaning the mixture. With richer mixtures, the available oxygen preferentially combines with the fuel to form carbon dioxide (CO_2) and water (H_2O), leaving less oxygen available to combine with nitrogen to form NOx. A mixture richer than stoichiometric will result in incomplete combustion. Nearly all the oxygen will then combine with the fuel, emissions of CO and VOC will increase, and reductions in peak temperatures will reduce NOx formation. There is a very rapid exponential increase in CO and VOC emissions as the mixture becomes richer than stoichiometric.

The use of very lean air/fuel ratios may result in ignition problems. For this reason, techniques designed to improve ignition are often combined with lean air/fuel ratios to control NOx emissions and avoid increases in VOC emissions. These other techniques are described on the following pages.

Typical Effectiveness: When leaning of the mixture is combined with other techniques such as low-emission combustion retrofit, NOx reductions greater than 80 percent are achievable, along with reductions in CO and VOC emissions. If extremely lean mixtures are used in conjunction with engine derating, NOx reductions well above 80 percent (less than 65 ppmv) are achievable. For extremely lean mixtures the resulting reduced temperatures will tend to inhibit oxidation, which will increase CO and VOC emissions to some degree.

For rich mixtures, the NOx reduction potential is not as great as reductions for lean mixtures. As the mixture is richened, emissions of CO and VOC increase to unacceptable levels before the NOx decreases to levels achieved by leaning the mixture.

Limitations: If the air/fuel mixture is richened excessively, emissions of CO and VOC increase dramatically. If the air/fuel ratio is leaned excessively, the flammability limit may be exceeded, resulting in misfiring. When an engine misfires (i.e., fails to fire), uncombusted fuel enters the exhaust, which dramatically increases VOC emissions.

Other Effects: None known.

Costs: Changing the air/fuel ratio of a SI engine should cost no more than $300. There is generally a fuel penalty for rich-burn engines that are richened, but leaning the mixture may reduce fuel consumption. These fuel effects vary with the engine and the degree of change in the air/fuel mixture.

3. Low-Emission Combustion/Precombustion Chamber Retrofit

Applicability: This control technology can be used on all SI engines, and has had wide applications on a variety of engines.

Principle: This method is used to enhance the effectiveness of the air/fuel ratio method described previously. As indicated previously in the discussion of air/fuel ratio changes, leaning the air/fuel mixture from the optimal NOx producing ratio will reduce NOx formation. The leaner the mixture, the lower the NOx emissions. However, to obtain substantial reductions in NOx emissions, engine modifications are needed to assure that the fuel will ignite and to minimize any fuel consumption penalties. A number of engine manufacturers and NOx control equipment manufacturers offer retrofit kits for some makes and models of lean-burn and rich-burn engines that allow these engines to operate on extremely lean mixtures to minimize NOx emissions. These retrofits are often referred to as low-emission combustion retrofits.

On smaller engines, the cylinder head and pistons can be redesigned to promote improved swirl patterns which result in thorough mixing. On larger engines, the use of a precombustion chamber (also referred to as a prechamber) is needed to ignite the lean mixture. Combustion begins in the smaller prechamber, which contains the spark plug and a rich air/fuel mixture. Combustion propagates into the larger main chamber, which contains a lean air/fuel mixture. The resulting peak temperatures are lower due to: 1) the rich ignition mixture, 2) heat transfer losses as combustion proceeds into the main chamber, and 3) the dilution effects of the excess air.

Many precombustion chamber retrofits consist of replacing the existing engine heads with new heads. However, some low cost prechamber retrofits are designed to use the existing engine's head, with the prechambers fitted into the existing spark plug hole. Other prechamber retrofits consist of a modified spark plug instead of a separate prechamber. The modified spark plug has a small, built-in fuel nozzle which injects fuel toward the spark plug electrode.

In order to achieve these leaner air/fuel ratios, additional amounts of air must be introduced into the engine when using a given amount of fuel. For naturally aspirated engines, a turbocharger often must be added to provide the additional air. In other cases, the existing turbocharger may have to be replaced or modified to increase the air throughput.

Other equipment may also be used in a low-emission combustion retrofit, such as a high energy ignition system to eliminate or minimize misfiring problems associated with lean operation, a new or modified aftercooler, and an air/fuel ratio controller. This equipment is described inmore detail on the following pages.

Typical Effectiveness: For natural gas-fired engines, in almost all cases NOx emissions can be reduced to less than 130 parts per million (ppm) (i.e., greater than an 80 percent reduction over uncontrolled levels) with little or no fuel penalty. If engine parameters are adjusted and carefully controlled and the maximum power output of the engine is derated, sustained emissions below 65 ppm are achievable.

Limitations: NOx reductions of roughly 80 percent over uncontrolled levels are achievable with little or no fuel penalty. However, if the engine is leaned further to reduce emissions by more than about 80 percent, the fuel penalty increases exponentially. In some cases, a turbocharger may be needed to provide increased air flow, but a properly sized turbocharger may not be available for a retrofit. In other cases, the available retrofit parts may not allow the engine to produce the same maximum power, and the engine must be derated. Beyond a certain degree of leaning (and NOx reduction), misfiring will become a problem.

In some cases, it may be cheaper to replace an existing engine with a new low-emission combustion engine, rather than install a retrofit kit. This is especially true if the retrofit kit has to be developed for that particular make and model of engine, or if the existing engine is old, inefficient, or unreliable.

Other Effects: At extremely lean air/fuel ratios, VOC and CO emissions tend to increase slightly. Once the air/fuel mixture is sufficiently lean, misfiring may occur, in which case VOC emissions can increase substantially.

Costs: For the installation of precombustion chamber heads and related equipment on large (~ 2,000 horsepower) engines, capital costs are about $400,000 per engine, and installation costs are about $200,000. Costs are lower for smaller engines. In terms of dollars per rated brake horsepower (bhp), costs are about $250/bhp for the large engines, and tend to be higher than this for smaller engines.

For prechambers fitted inside the existing spark plug hole, capital costs are about $15,000 to $20,000 for engines in the 300 to 400 horsepower range. Capital costs for engines in the 2,000 horsepower range can exceed $200,000.

4. Ignition System Improvements

Applicability: This control technology can be used on all SI engines. It has been applied to only a limited number of engines and engine types.

Principle: This method is used in conjunction with the use of lean air/fuel ratios to reduce NOx emissions. It allows leaner mixtures to be used without misfiring problems. As indicated previously, the leaner the air/fuel ratio, the lower the NOx emissions. However, at some point in leaning the mixture, lean misfire begins to occur, and further NOx reductions are impractical. In most engines during ignition, a nonuniform air/fuel mixture passes by the spark plug. In standard ignition systems, the spark plug's firing duration is extremely short. If the spark plug fires when this mixture is too lean to support combustion, a misfire occurs. If the spark plug fires multiple times, or for a longer period of time, there is a greater chance that the proper air/fuel mixture will pass by the spark plug and ignite the mixture. Improved ignition systems generally use a higher voltage to fire the spark plug, in addition to multiple or continuous sparking of the spark plug. This allows the use of leaner air/fuel ratios, resulting in lower NOx emissions.

Typical Effectiveness: Emission reductions from a combination of leaning of the air/fuel mixture and use of a continuous sparking ignition system approach but are generally less than a pre-combustion chamber retrofit. NOx emissions can generally be reduced to about 200 ppm.

Limitations: If the air/fuel ratio is leaned excessively, misfiring can occur. As with all methods involving leaning, the engine's maximum power rating may have to be reduced unless a turbocharger is retrofitted to naturally aspirated engines or the existing turbocharger is modified or replaced to increase the throughput of combustion air. In many cases, a separate retrofit kit must be developed for each make and model of engine, and only a few kits have been developed so far.

Other Effects: At extremely lean air/fuel ratios, VOC and CO emissions tend to increase slightly. If the air/fuel mixture is leaned excessively, misfiring may occur, in which case VOC emissions can increase substantially.

Costs: Costs are about two-thirds that of a pre-combustion chamber retrofit involving head replacement. For large engines (~ 2000 horsepower), costs can be in excess of $200,000.

5. Turbocharging or Supercharging and Aftercooling

Applicability: This control method can be used on almost any engine and is widely used.

Principle: Turbochargers and superchargers compress the intake air of an engine before this air enters the combustion chamber. Due to compression, the temperature of this air is increased. This tends to increase peak temperatures, which increases the formation of NOx. However, the heat sink effect of the additional air in the cylinder, combined with the increased engine efficiency from turbocharging or supercharging, generally results in a minor overall decrease in NOx emissions per unit of power output. On the other hand, turbocharging or supercharging can significantly increase the maximum power rating of an engine, which increases the maximum mass emissions rate for NOx. Due to the high density of oxygen in the combustion chamber, turbocharging or supercharging makes the combustion process more effective, which tends to reduce emissions of CO and VOC.

On turbocharged or supercharged engines, the intake air temperature can be reduced by aftercooling (also known as intercooling or charge air cooling). An aftercooler consists of a heat exchanger located between the turbocharger or supercharger and combustion chamber. The heat exchanger reduces the temperature of the intake air after it has been compressed by the supercharger or turbocharger. Cooling the intake air reduces peak combustion temperatures, and thereby reduces NOx emissions. The cooling medium can be water, either from the radiator or from a source outside of the engine, or the cooling medium can be ambient air. The use of radiator water generally results in the least amount of cooling, while the use of outside water or ambient air results in the most cooling of the intake air. Using either a cooler source of water or ambient air for the aftercooler can reduce the intake air temperature to as low as 90 °F.

The cooling effects of the aftercooler increases the density of the intake air, which results in a leaner air/fuel mixture in SI engines if no additional fuel is introduced. For engines already using lean air/fuel mixtures, this leaner mixture will lower NOx emissions further.

Typical Effectiveness: NOx reductions from aftercooling range from about 3 to 35 percent. The percentage reduction is roughly proportional to the reduction in temperature. Reductions in VOC and CO emissions also occur.

Limitations: Turbochargers or superchargers may not be available for some engines. In addition, some internal engine parts may have to be replaced or strengthened when adding a supercharger or turbocharger.

Other Effects: Use of a supercharger or turbocharger increases the efficiency and maximum power rating of an engine. Use of an aftercooler further increases the efficiency of an engine, and can also increase the maximum power rating. At low loads and excessive temperature reductions, an aftercooler can cause longer ignition delays, which increase emissions of VOC and particulate matter. This emissions increase can be minimized if an aftercooler bypass is used to limit cooling at low loads.

Costs: The cost of retrofitting a naturally aspirated engine with a turbocharger and related equipment varies from engine to engine. These costs vary not only because different sizes of turbochargers are used for different engines, but also because different engines may require more extensive internal modifications.

For natural gas engines, costs of a turbocharger retrofit are typically $30,000 to $40,000 for engines in the 800 to 900 horsepower range. For natural gas engines in the 1,100 to 1,300 horsepower range, costs can vary from $35,000 to $150,000.

In some cases, replacement of an existing engine with a new, low NOx emitting turbocharged engine may result in lower overall costs than retrofitting the existing engine with a turbocharger or supercharger. Although the capital cost of the new engine will generally be greater than the retrofit cost for the existing engine, the new engine will reduce overall costs due to increased efficiency, reduced down time, and reduced maintenance and repair costs.

Except in cases where an engine's usage factor is very low, the improved fuel efficiency associated with the use of turbochargers, superchargers, and aftercoolers generally results in a cost savings.

6. Exhaust Gas Recirculation

Applicability: Exhaust gas recirculation, or EGR, can be used on all engine types. It has been widely used on gasoline motor vehicle engines, but has been used infrequently on engines used in other applications.

Principle: EGR can be external or internal. In the case of external EGR, a portion of the exhaust gas is diverted from the exhaust manifold and routed to the intake manifold before reentering the combustion chamber. For internal EGR, an engine's operating parameters (such as valve timing or supercharger pressure) are adjusted so that a greater amount of exhaust remains in the cylinder after the exhaust stroke.

EGR reduces NOx emissions by decreasing peak combustion temperatures through two mechanisms: dilution and increased heat absorption. Dilution of the fuel/air mixture slows the combustion process, thereby reducing peak temperatures. In addition, exhaust gases contain significant amounts of carbon dioxide and water vapor, which have a higher heat capacity than air. This means that, compared to air, carbon dioxide and water vapor can absorb greater amounts of heat without increasing as much in temperature.

Typical Effectiveness: NOx reductions are limited to about 30 percent before operation of the engine is adversely affected.

Limitations: EGR will reduce an engine's peak power. This may be a serious problem for engines required to operate at or near their peak power rating. The EGR system must be designed and developed for each make and model of engine. An EGR retrofit kit is not available for most engines.

Other Effects: EGR reduces engine efficiency. For example, fuel efficiency decreases about 2 percent for a 12 percent decrease in NOx emissions.

Costs: Costs are typically greater than for timing retard, but less than a turbocharger retrofit.

7. Prestratified Charge

Applicability: This control technology is applicable to spark-ignited rich-burn engines. This method converts rich-burn engines into lean burn engines. It has been used on a number of different engines, but is not as widely used as some of the most popular controls, such as low emission combustion or NSCR catalysts.

Principle: Rich-burn engines are typically four stroke naturally aspirated engines with no intake/exhaust overlap. The major components of a prestratified charge (PSC) retrofit are the air injectors. These injectors pulse air into the intake manifold in such a fashion that layers or zones of air and the air/fuel mixture are introduced into the combustion chamber. Once inside the combustion chamber, the top zone, near the spark plug, contains a rich air/fuel mixture. The bottom zone is an air layer. The most recent version of the PSC system operates off of engine vacuum, which allows the system to automatically compensate for varying power outputs.

The PSC technique is very similar in concept to a precombustion chamber. Both have a rich fuel mixture near the spark plug, and a lean mixture elsewhere in the combustion chamber. NOx emissions are low for PSC for the same reasons they are low for prechamber designs.

Typical Effectiveness: PSC can achieve greater than 80 percent control of NOx for power outputs up to about 70 or 80 percent of the maximum (uncontrolled) power rating using air injection only.

Limitations: In order for the engine to generate more than 70 or 80 percent of the maximum (uncontrolled) power rating, the air injection rate must be reduced. This results in a richer fuel mixture, which increases NOx emissions. To maintain high NOx control at high power outputs, a turbocharger may have to be added or the existing turbocharger may have to be modified or replaced to increase air throughput. Maximum emission reductions, even with use of a turbocharger, are generally lower than can be accomplished with the use of an NSCR catalyst.

Other Effects: Fuel efficiency may be improved because PSC effectively converts a rich-burn engine into a lean-burn engine.

Costs: For engines in the 300 to 900 horsepower range, retrofit costs are typically about $30,000. For engines in the 1100 to 1600 horsepower range, retrofit costs are about $40,000. However, costs can double if a turbocharger is added. Retrofits for even larger engines where a turbocharger is added can cost as much as $160,000 to $190,000.

B. Fuel Switching

NOx emissions from IC engines can be reduced by switching to fuels that burn at lower temperatures, such as methanol.

1. Methanol

Applicability: This control method is applicable to all engine types. Although a number of motor vehicle engines have been converted to methanol fuel, very few stationary source engine conversions have taken place.

Principle: NOx emissions are generally lower for methanol than for other fuels for several reasons. Methanol has a higher heat of vaporization than other fuels, and thus the process of vaporization cools the air/fuel mixture significantly, resulting in lower peak temperatures. Methanol, being a partially oxygenated fuel, burns with a lower flame temperature, which also reduces peak temperatures. Methanol fuel consists of only one type of molecule, which makes it easier to optimize the combustion process in comparison to fuels consisting of a wide variety of molecules, such as gasoline or diesel. Methanol and natural gas combustion produces almost no particulate matter.

For rich-burn methanol engines, a relatively inexpensive three-way catalyst like that used in gasoline-engined motor vehicles can be installed to control NOx. Methanol can also be used as a fuel for lean-burn spark-ignited engines. Methanol has a wider range of flammability than many other fuels, allowing a leaner mixture to be used, resulting in greater NOx reductions than is possible with other fuels.

Methanol can be used as a replacement fuel for gaseous and gasoline fueled engines with only relatively minor engine modifications.

Typical Effectiveness: NOx reductions from the conversion of an engine to methanol fuel depend on the pre-conversion engine and fuel type. NOx reductions range from about 30 percent for the conversion of a natural gas engine. Reductions are even greater when the conversion is accompanied by the addition of a catalyst.

Limitations: A retrofit kit must be developed for each make and model of engine. Currently, there are very few conversion kits available. The fuel and engine system must use materials that are resistant to the corrosive action of methanol. Special lubricants must be used to avoid excessive engine wear. Incomplete combustion of methanol produces formaldehyde, but the use of an oxidation catalyst can reduce formaldehyde emissions to low levels.

Other Effects: None for SI engines.

Costs: Conversion costs for an automotive engine are on the order of $1,000. Costs for converting stationary gasoline engines to methanol are expected to be similar. The largest cost element is often is the fuel price differential between methanol and the fuel it replaces (e.g. natural gas or gasoline). Included in this price differential are transportation, storage, and refueling costs associated with the use of methanol.

C. Post Combustion Controls

Post combustion controls generally consist of catalysts or filters that act on the engine exhaust to reduce emissions. Post combustion controls also include the introduction of agents or other substances that act on the exhaust to reduce emissions, with or without the assistance of catalysts or filters.

1. Oxidation Catalyst

Applicability: This control method is applicable to all engines. For stationary engines, oxidation catalysts have been used primarily on lean-burn engines. Rich-burn engines tend to use 3-way catalysts, which combine nonselective catalytic reduction (NSCR) for NOx control and an oxidation catalyst for control of CO and VOC. The oxidation catalyst has been used on lean-burn engines for nearly 30 years. Oxidation catalysts are used less frequently on stationary engines. In the United States, only about 500 stationary lean-burn engines have been fitted with oxidation catalysts.

Principle: An oxidation catalyst contains materials (generally precious metals such as platinum or palladium) that promote oxidation reactions between oxygen, CO, and VOC to produce carbon dioxide and water vapor. These reactions occur when exhaust at the proper temperature and containing sufficient oxygen passes through the catalyst. Depending on the catalyst formulation, an oxidation catalyst may obtain reductions at temperatures as low as 300 or 400 $_o$F, although minimum temperatures in the 600 to 700 $_o$F range are generally required to achieve maximum reductions. The catalyst will maintain adequate performance at temperatures typically as high as 1350 $_o$F before problems with physical degradation of the catalyst occur. In the case of rich-burn engines, where the exhaust does not contain enough oxygen to fully oxidize the CO and VOC in the exhaust, air can be injected into the exhaust upstream of the catalyst.

Typical Effectiveness: The effectiveness of an oxidation catalyst is a function of the exhaust temperature, oxygen content of the exhaust, amount of active material in the catalyst, exhaust flow rate through the catalyst, and other parameters. Catalysts can be designed to achieve almost any control efficiency desired. Reductions greater than 90 percent for both CO and VOC are typical. Reductions in VOC emissions can vary significantly and are a function of the fuel type and exhaust temperature.

Limitations: A sufficient amount of oxygen must be present in the exhaust for the catalyst to operate effectively. In addition, the effectiveness of an oxidation catalyst may be poor if the exhaust temperature is low, which is the case for an engine at idle. Oxidation catalysts, like other catalyst types, can be degraded by masking, thermal sintering, or chemical poisoning by sulfur or metals. If the engine is not in good condition, a complete engine overhaul may be needed to ensure proper catalyst performance.

Sulfur, which can be found in fuels and lubricating oils, is generally a temporary poison, and can be removed by operating the catalyst at sufficiently high temperatures. However, high temperatures can damage the substrate material. Other ways of dealing with sulfur poisoning include the use of low sulfur fuels or scrubbing of the fuel to remove the sulfur. Besides being a catalyst poison, sulfur can also be converted into sulfates by the catalyst before passing through the exhaust pipe. Catalysts can be specially formulated to minimize this conversion, but these special formulations must operate over a relatively narrow temperature range if they are to effectively reduce VOC and CO and also suppress the formation of sulfates. For engines operated over wide power ranges, where exhaust temperatures vary greatly, special catalyst formulations are not effective.

Metal poisoning is generally more permanent, and can result from the metals present in either the fuel or lubricating oil. Specially formulated oils with low metals content are generally specified to minimize poisoning, along with good engine maintenance practices. Metal poisoning can be reversed in some cases with special procedures. Many catalysts are now formulated to resist poisoning.

Masking refers to the covering and plugging of a catalyst's active material by solid contaminants in the exhaust. Cleaning of the catalyst can remove these contaminants, which usually restores catalytic activity. Masking is generally limited to engines using landfill gas, diesel fuel, or heavy liquid fuels, although sulfate ash from lubricating oil may also cause masking. Masking can be minimized by passing the exhaust through a particulate control device, such as a filter or trap, before this material encounters the catalyst. In the case of landfill gas, the particulate control device can act directly on the fuel before introduction into the engine.

Thermal sintering is caused by excessive heat and is not reversible. However, it can be avoided by incorporating over temperature control in the catalyst system. Many manufacturers recommend the use of over temperature monitoring and control for their catalyst systems. In addition, stabilizers such as CeO_2 or La_2O_3 are often included in the catalyst formulation to minimize sintering. High temperature catalysts have been developed which can withstand temperatures exceeding 1800 $_o$F for some applications. This temperature is well above the highest IC engine exhaust temperature that would ever be encountered. Depending on the design and operation, peak exhaust temperatures for IC engines range from 550 to 1300 $_o$F.

Other recommendations to minimize catalyst problems include monitoring the pressure drop across the catalyst, the use of special lubricating oil to prevent poisoning, periodic washing of the catalyst, the monitoring of emissions, and the periodic laboratory analysis of a sample of catalyst material.

Other Effects: A catalyst will increase backpressure in the exhaust, resulting in a slight reduction in engine efficiency and maximum rated power. However, when conditions require an exhaust silencer, the catalyst can often be designed to do an acceptable job of noise suppression so that a separate muffler is not required. Under such circumstances, backpressure from the catalyst may not exceed that of a muffler, and no reduction in engine efficiency or power occur. Often, engine manufacturers rate their engines at a given backpressure, and as long as the catalyst does not exceed this backpressure, no reduction in the engine's maximum power rating will be experienced.

Costs: Typical costs for an oxidation catalyst are 10 to 12 dollars per horsepower, or slightly less than a nonselective catalytic reduction (NSCR) catalyst. The cost for catalyst wash service has been reported as $300 to $600 per cubic foot of catalyst material.

2. Nonselective Catalytic Reduction (NSCR)

Applicability: This control method is applicable to all rich-burn engines, and is probably the most popular control method for rich-burn engines. The first wide scale application of NSCR technology occurred in the mid- to late-1970s, when 3-way NSCR catalysts were applied to motor vehicles with gasoline engines. Since then, this control method has found widespread use on stationary engines. NSCR catalysts have been commercially available for stationary engines for over 15 years, and over 3,000 stationary engines in the U.S. are now equipped with NSCR controls. Improved NSCR catalysts, called 3-way catalysts because CO, VOC, and NOx are simultaneously controlled, have been commercially available for stationary engines for over 10 years. Over 1,000 stationary engines in the U.S. are now equipped with 3-way NSCR controls.

The dual bed NSCR catalyst is a variation of the 3-way catalyst. The dual bed contains a reducing bed to control NOx, followed by an oxidizing bed to control CO and VOC. Dual bed NSCR catalysts tend to be more effective than 3-way catalysts, but are also more expensive, and have not been applied to as many engines as 3-way catalysts. Improved 3-way catalysts can approach the control efficiencies of dual bed catalysts at a lower cost, and for this reason dual bed catalysts have lost popularity to 3-way catalysts.

Principle: The NSCR catalyst promotes the chemical reduction of NOx in the presence of CO and VOC to produce oxygen and nitrogen. The 3-way NSCR catalyst also contains materials that promote the oxidation of VOC and CO to form carbon dioxide and water vapor. To control NOx, CO, and VOC simultaneously, 3-way catalysts must operate in a narrow air/fuel ratio band (15.9 to 16.1 for natural gas-fired engines) that is close to stoichiometric. An electronic controller, which includes an oxygen sensor and feedback mechanism, is often necessary to maintain the air/fuel ratio in this narrow band. At this air/fuel ratio, the oxygen concentration in the exhaust is low, while concentrations of VOC and CO are not excessive.

For dual bed catalysts, the engine is run slightly richer than for a 3-way catalyst. The first catalyst bed in a dual bed system reduces NOx. The exhaust then passes into a region where air is injected before entering the second (oxidation) catalyst bed. NOx reduction is optimized in comparison to a 3-way catalyst due to the higher CO and VOC concentrations and lower oxygen concentrations present in the first (reduction) catalyst bed. In the second (oxidation) bed, CO and VOC reductions are optimized due to the relatively high oxygen concentration present. Although the air/fuel ratio is still critical in a dual bed catalyst, optimal NOx reductions are achievable without controlling the air/fuel ratio as closely as in a 3-way catalyst.

Typical Effectiveness: Removal efficiencies for a 3-way catalyst are greater than 90 percent for NOx, greater than 80 percent for CO, and greater than 50 percent for VOC. Greater efficiencies, below 10 parts per million NOx, are possible through use of an improved catalyst containing a greater concentration of active catalyst materials, use of a larger catalyst to increase residence time, or through use of a more precise air/fuel ratio controller.

For dual bed catalysts, reductions of 98 percent for both NOx and CO are typical.

The previously mentioned reduction efficiencies for catalysts are achievable as long as the exhaust gases are within the catalyst temperature window, which is typically 700 to 1200 $_{o}$F. For many engines, this temperature requirement is met at all times except during startup and idling.

The percentage reductions are essentially independent of other controls that reduce the NOx concentration upstream of the catalyst. Thus, a combination of combustion modifications and catalyst can achieve even greater reductions.

Limitations: As with oxidation catalysts, NSCR catalysts are subject to masking, thermal sintering, and chemical poisoning. In addition, NSCR is not effective in reducing NOx if the CO and VOC concentrations are too low. NSCR is also not effective in reducing NOx if significant concentrations of oxygen are present. In this latter case, the CO and VOC in the exhaust will preferentially react with the oxygen instead of the NOx. For this reason, NSCR is an effective NOx control method only for rich-burn engines.

When applying NSCR to an engine, care must be taken to ensure that the sulfur content of the fuel gas is not excessive. The sulfur content of pipeline-quality natural gas and LPG is very low, but some oil field gases and waste gases can contain high concentrations. Sulfur tends to collect on the catalyst, which causes deactivation. This is generally not a permanent condition, and can be reversed by introducing higher temperature exhaust into the catalyst or simply by heating the catalyst. Even if deactivation is not a problem, the water content of the fuel gas must be limited when significant amounts of sulfur are present to avoid deterioration and degradation of the catalyst from sulfuric acid vapor.

For dual bed catalysts, engine efficiency suffers slightly compared to a 3-way catalyst due to the richer operation of engines using dual bed catalysts.

In cases where an engine operates at idle for extended periods or is cyclically operated, attaining and maintaining the proper temperature may be difficult. In such cases, the catalyst system can be designed to maintain the proper temperature, or the catalyst can use materials that achieve high efficiencies at lower temperatures. For some cyclically operated engines, these design changes may be as simple as thermally insulating the exhaust pipe and catalyst.

Most of these limitations can be eliminated or minimized by proper design and maintenance. For example, if the sulfur content of the fuel is excessive, the fuel can be scrubbed to remove the sulfur, or the catalyst design or engine operation can be modified to minimize the deactivation effects of the sulfur. Poisoning from components in the lube oil can be eliminated by using specially formulated lube oils that do not contain such components. However, NSCR applications on landfill gas and digester gas have generally not been successful due to catalyst poisoning and plugging from impurities in the fuel.

Other Effects: A very low oxygen content in the exhaust must be present for NSCR to perform effectively. To achieve this low oxygen content generally requires richening of the mixture. This richening tends to increase CO and VOC emissions. However, use of a 3-way catalyst can reduce CO and VOC emissions to levels well below those associated with uncontrolled engines.

Another effect of NSCR is increased fuel consumption. This increase is very slight when compared to an uncontrolled rich-burn engine. However, when compared to a lean-burn engine, a rich-burn engine uses 5 to 12 percent more fuel for the same power output. If a rich-burn engine uses a dual bed catalyst, a further slight increase in fuel consumption is generally experienced.

Costs: The total installed cost of an NSCR system on an existing engine varies with the size of the engine. The catalyst will cost about 8 to 15 dollars per horsepower, while air/fuel ratio controllers vary in cost from about $3,500 to $7,000. Installation and labor costs generally range from $1,000 to $3,000. For an 80 horsepower engine, total costs for installation may range from $5,000 to $11,000. For an 1,100 horsepower engine, installed costs of $20,000 to $25,000 are typical.

3. Hybrid System

Applicability: This control method can be applied to all engines. This control method was conceived by Radian Corporation, and has been developed by AlliedSignal and Beaird Industries. There has been one field prototype demonstration in San Diego, and it appears that the system has been offered commercially. However, there are no commercial applications of this technique.

Principle: The hybrid system is a modification of the dual bed NSCR system. The hybrid system adds a burner in the engine exhaust between the engine and the dual bed catalysts. The burner is operated with an excess amount of fuel so that oxygen within the engine exhaust is almost completely consumed, and large amounts of CO are generated. The exhaust then passes through a heat exchanger to reduce temperatures before continuing on to a reducing catalyst. The NOx reduction efficiency of the reducing catalyst is extremely high due to the high CO concentration (the CO acts as a reducing agent to convert NOx into nitrogen gas. The exhaust next passes through another heat exchanger, and air is added before the exhaust passes through an oxidation catalyst. The oxidation catalyst is extremely efficient in reducing CO and VOC emissions due to the excess oxygen in the exhaust.

Typical Effectiveness: NOx concentrations as low as 3 to 4 ppm are achievable with this system. Concentrations of CO and VOC are typical of systems using oxidation catalysts.

Limitations: When the oxygen content of the engine's exhaust is high, such as for lean-burn engines, the burner must use a large amount of fuel to consume nearly all the oxygen and generate sufficient amounts of CO. Therefore, use of this method on lean-burn engines is only practical in cogeneration applications, where heat generated by the burner can be recovered and converted to useful energy.

Other Effects: For rich-burn engines, this method has a fuel penalty of about one to five percent. However, for lean-burn engines, the fuel penalty could be equal to the uncontrolled engine's fuel consumption.

Costs: Costs are several times greater than for a simple NSCR catalyst. Capital costs were reported in 1993 as $150,000 for a 470 brake horsepower engine.

4. Selective Catalytic Reduction (SCR)

Applicability: This method was patented in the U.S. in the 1950s, and there have been over 700 applications of SCR to combustion devices worldwide. Some of these applications include stationary IC engines. However, most of these applications are external combustion devices such as boilers. SCR systems for IC engines have been commercially available for a number of years, but there have only been a few dozen SCR retrofits of IC engines. SCR is applicable to all lean-burn engines, including diesel engines.

Principle: The exhaust of lean-burn engines contains high levels of oxygen and relatively low levels of VOC and CO, which would make an NSCR type of catalyst ineffective at reducing NOx. However, an SCR catalyst can be highly effective under these conditions. Oxygen is a necessary ingredient in the SCR NOx reduction equation, and SCR performs best when the oxygen level in the exhaust exceeds 2 to 3 percent.

Differing catalyst materials can be used in an SCR catalyst, depending on the exhaust gas temperature. Base metal catalysts are most effective at exhaust temperatures between 500 and 900 °F. Base metal catalysts generally contain titanium dioxide and vanadium pentoxide, although other metals such as tungsten or molybdenum are sometimes used. Zeolite catalysts are most effective at temperatures between 675 to over 1100 °F. Precious metal catalysts such as platinum and palladium are most effective at temperatures between 350 and 550 °F.

In SCR, ammonia (or, in some cases, urea) is injected in the exhaust upstream of the catalyst. The catalyst promotes the reaction of ammonia with NOx and oxygen in the exhaust, converting the reactants to water vapor and nitrogen gas. Ammonia injection can be controlled by the use of a NOx monitor in the exhaust downstream of the catalyst. A feedback loop from the monitor to the ammonia injector controls the amount injected, so that NOx reductions are maximized while emissions of ammonia are minimized. To eliminate the use of a costly NOx monitor, some applications use an alternative system that measures several engine parameters. Values for these parameters are then electronically converted into estimated NOx concentrations.

Typical Effectiveness: The NOx removal efficiency of SCR is typically above 80 percent when within the catalyst temperature window.

Limitations: SCR can only be used on lean burn engines. Relatively high capital costs make this method too expensive for smaller or infrequently operated engines.

Some SCR catalysts are susceptible to poisoning from metals or silicon oxides that may be found in the fuel or lubricating oil. Poisoning problems can be minimized by using specially formulated lubricating oils that do not contain the problem metals, the use of fuels with low metals or silicon oxides content, or the use of zeolite catalysts which are not as susceptible to poisoning.

If platinum or palladium is used as an active catalyst material, the sulfur content of the exhaust must be minimized to avoid poisoning of the catalyst. In addition, for all types of SCR catalysts, high sulfur fuels will result in high sulfur oxides in the exhaust. These sulfur compounds will react with the ammonia in the exhaust to form particulate matter that will either mask the catalyst or be released into the atmosphere. These problems can be minimized by using low sulfur fuel, a metal-based SCR system specially designed to minimize formation of these particulate matter compounds, or a zeolite catalyst.

Ammonia gas has an objectionable odor, is considered an air pollutant at low concentrations, becomes a health hazard at higher concentrations, and is explosive at still higher concentrations. Safety hazards can occur if the ammonia is spilled or there are leaks from ammonia storage vessels. These safety hazards can be minimized by taking proper safety precautions in the design, operation, and maintenance of the SCR system. Safety hazards can be substantially reduced by using aqueous ammonia or urea instead of anhydrous ammonia. If a concentrated aqueous solution of urea is used, the urea tank must be heated to avoid recrystallization of the urea. In addition, if too much ammonia is injected into the exhaust, excessive ammonia emissions may result. These emissions can be reduced to acceptable levels by monitoring and controlling the amount of ammonia injected into the exhaust.

SCR may also result in a slight increase in fuel consumption if the backpressure generated by the catalyst exceeds manufacturer's limits.

Other Effects: None known.

Costs: SCR is one of the higher cost control methods due to the capital cost for the catalyst, the added cost and complexity of using ammonia, and the instrumentation and controls needed to carefully monitor NOx emissions and meter the proper amount of ammonia. Estimated costs, however have been declining over the past several years. Currently, costs are estimated to be about $50 to $125 per horsepower.

Engines operated at a constant load may be able to eliminate the NOx monitor and feedback ammonia metering system. In such cases, proper instrumentation must be used to monitor ammonia and NOx when the SCR system is set up. Frequent checks are also needed to assure that the setup does not change. Such a system was purchased in 1996 for a 1,300 horsepower diesel engine at a cost of approximately $100,000.

5. Lean NOx Catalyst

Applicability: This control method can be used on any lean-burn engine, although development work has concentrated on diesel engines. This control method is still in the development stage and is not commercially available, but may be available in a few years.

Principle: A number of catalyst materials can be used in the formulation of lean NOx catalysts. The constituents are generally proprietary. NOx reductions are generally minimal unless a reducing agent (typically raw fuel) is injected upstream of the catalyst to increase catalyst performance to acceptable levels. Depending on the catalyst formulation, this method can reduce NOx, CO, and VOC simultaneously.

Typical Effectiveness: Claims for NOx control efficiencies have ranged from 25 to 50 percent. Steady state testing on a diesel-fueled engine yielded NOx reductions of 17 to 44 percent.

Limitations: Use of a reducing agent increases costs, complexity, and fuel consumption. The reducing agent injection system must be carefully designed to minimize excess injection rates. Otherwise, emissions of VOC and particulate matter can increase to unacceptable levels. Tests have shown that lean NOx catalysts produce significant amounts of nitrous oxide (N_2O), and that this production increases with increasing NOx reduction efficiencies and reducing agent usage. This method is not commercially available, and is still in the development and demonstration stage.

Other Effects: None known.

Costs: Since no systems have been sold commercially, costs are unknown, but would probably exceed those for NSCR.

6. NOxTech

Applicability: This control method, formerly known as RAPRENOX, is applicable to lean-burn engines. This technology can be applied to lean-burn gaseous fueled engines. However, this technology is relatively new, and there have only been a few commercial applications.

Principle: NOxTech uses a gaseous phase autocatalysis process to reduce NOx and other pollutants. There is no catalyst. In this method a reagent and fuel are injected into a reactor vessel with the exhaust stream of the engine. The fuel combusts and increases the exhaust temperature to a range of 1,400 to 1,550 $_{o}$F, where reactions between nitric oxide (NO) and the reagent generate N_2, CO_2, and H_2O. The reactor vessel is a large chamber which increases the residence time of the constituent gases at high temperature. In the past, cyanuric acid has been the reagent. More recent literature indicates that either urea or ammonia is used.

Typical Effectiveness: NOx emission reductions of 80 to 90 percent are typical, and the system can be designed to reduce NOx by well over 90 percent. This control method also removes 80 percent or more of CO, VOCs, and PM as well with minimal reagent slip.

Limitations: With a recovery heat exchanger in the reactor, the fuel penalty is about 5 to 10 percent. There are versions which do not have the heat exchanger. In these versions, significant amounts of fuel are used to heat the exhaust. Although this technology may be economically attractive for cogeneration applications where the energy used to heat the exhaust is recovered, the economics are less favorable for applications where the exhaust heat is not recovered. This technology may not be economically attractive when an engine's power output remains below 50 percent of full power. At low power outputs, exhaust temperatures are low, and greater amounts of fuel must be used to achieve the required exhaust temperature. The size of the reaction chamber may make applications difficult where there is a lack of room.

Other Effects: None known.

Costs: In general, the capital costs for this system are much lower than SCR, but operating costs are significantly higher. Start-up costs are estimated to be in the range of $100 to $200 per kilowatt.

7. Urea Injection

Applicability: This control method is applicable to all lean-burn engines and is also known as selective noncatalytic reduction. It has been used on several boilers to control NOx, but there have been no applications to internal combustion engines.

Principle: Urea injection is very similar to cyanuric acid injection, as both chemicals come in powder form, and both break down at similar temperatures to form compounds which react with nitric oxide. Differences are that a high temperature heating system is not required for urea injection. Instead, the urea is usually dissolved in water, and this solution is injected into the exhaust stream.

Typical Effectiveness: Unknown.

Limitations: The temperature window for urea is higher than the highest exhaust temperature of nearly all engines. Therefore, due to cost-effectiveness considerations, practical applications of urea injection are limited to engines in cogeneration applications. Specifically, these applications are limited to situations where supplemental firing is applied to the engine's exhaust to increase its temperature, and the exhaust heat is recovered and used.

Other Effects: Unknown.

Costs: Unknown.

8. NOx Adsorber Technology (SCONOx)

Applicability: This NOx control method is applicable to diesel-fueled and lean burn engines and is just entering the commercialization phase. It has been installed on gas turbines, boilers, and steam generators previously. The first U.S. application of NOx adsorber technology on a mobile source is the Honda Insight which is a hybrid vehicle. Multiple companies and organizations are engaged in the development of the NOx adsorber technology. This discussion will focus on SCONOx.

Principle: This system uses a single catalyst for the removal of NOx, VOC, and CO emissions. This is a three step process in which initially the catalyst simultaneously oxidizes NO, hydrocarbon, and CO emissions. In the second phase, NO_2 is absorbed into the catalyst surface through the use of a potassium carbonate coating. Unlike SCR, this technology does not require a reagent such as ammonia or urea in reducing emissions. Finally, the catalyst undergoes regeneration periodically to maintain maximum NOx absorption. The SCONOx system requires natural gas, water, and electricity and operates at temperatures ranging from 300? to 700? F.

The catalyst is regenerated by passing a dilute hydrogen reducing gas across its surface in the absence of oxygen. The gases react with the potassium nitrites and nitrates to form potassium carbonate which is the absorber coating on the surface of the catalyst. The exhaust from the regeneration process is nitrogen and steam. This catalyst has multiple sections of catalyst. At any given time, a certain percentage of the sections are in the oxidation/absorption cycle while the remaining catalyst sections are being regenerated. In IC engine applications, one regeneration approach has been to de-sorb the adsorber by running the engine in a fuel rich mode and passing the exhaust through a three way catalyst to reduce the NOx.

Typical Effectiveness: Since this technology is just entering commercialization data is very limited. Feasibility testing conducted by the manufacturer on a diesel engine rated less than 100 horsepower indicated that NOx reductions greater than 90 percent can be achieved. The manufacturer intends to conduct further testing on a demonstration basis. As part of its demonstration for California Environmental Technology Certification, this technology had NOx emissions of 2 ppmv (approximately 98.6% control) on a natural gas-fired gas turbine.

Limitations: The system is sensitive to trace amounts of sulfur in the exhaust. In certifying this technology with a gas turbine, it has been reported that the system achieves it lowest NOx levels by adding a sulfur scrubber to the natural gas fuel. From this statement, it would seem logical that the use of low sulfur diesel fuel would be recommended on IC engines.

Other Effects: Since a reagent is not required as with SCR, there will be no emissions of ammonia which is a toxic compound which can cause health effects. The catalyst is regenerated using hydrogen gas which is generated onsite through the use of a reformer. Hydrogen is flammable and could be a potential safety hazard.

Costs: At this stage of development/commercialization, the cost for a single prototype is estimated to be about $100,000. It is expected that mass production would drop prices substantially.

D. Replacement

Another method of reducing NOx is to replace the existing IC engine with an electric motor, or a new engine designed to emit very low NOx emissions. In some instances, the existing engine may be integral with a compressor or other gear, and replacement of the engine will require the replacement or modification of this other equipment as well.

Applicability: This control method is applicable to all engines.

Principle: Rather than applying controls to the existing engine, it is removed and replaced with either a new, low emissions engine or an electric motor.

Typical Effectiveness: New, low emissions engines can reduce NOx by a substantial amount over older, uncontrolled engines. Potential NOx reductions of over 60 percent can be realized by replacing existing SI engines with new certified low emission engines fueled by natural gas or propane.

Another approach is to replace an engine with an electric motor. An electric motor essentially eliminates NOx emissions associated with the removed engine, although there may be minor increases in power plant emissions to supply electricity to the electric motor.

Limitations: In remote locations or where electrical infrastructure is inadequate, the costs of electrical power transportation and conditioning may be excessive. Similarly, the cost of replacing an engine with a natural gas fired unit could be prohibitive if a natural gas pipeline is not in reasonably close proximity to the engine. In cases where the existing engine operates equipment integral to the engines (such as some engine/compressors that share a common crankshaft), both the engine and integral equipment often must be replaced.

Certified Engines: Another issue to consider is associated with new engines certified to an on road or off road emission standard. A certified engine's NOx emission units is given in g/bhp-hr and is an average of the NOx concentrations measured under different operating conditions of a given test cycle. So the certified engine's NOx emissions could be higher or lower than its certification value depending on the operating mode under which the engine is being tested. In addition, on road test cycles are typically transient in nature which matches the duty cycle of a mobile source whereas an off road cycle is steady state in nature. There is the possibility that the emissions measured using ARB Test Method 100 or U.S. EPA Test Method 7E on a certified engine in a stationary application may not match the engine's NOx certification numbers due to the differences between test cycles and the engine's operational duty cycle.

Other Effects: None known.

Costs: Costs of engine replacement with an electric motor or new low emissions engine are highly variable, and depend on the size of the engine, the cost of electricity, electrical power availability, accessibility of natural gas pipelines, useful remaining life for the existing engine, and other factors.

APPENDIX E

Stakeholders' Demonstration Program

Introduction

The stakeholders group conducted a program to demonstrate the degree of emission control that is feasible on rich-burn engines using currently available technologies. A primary objective of the program was to demonstrate that modern AFRCs could maintain emissions compliance and detect and alarm to non-compliance. This group, known as the Rule 1110.2 Industry Stakeholder Work Group, which included engine owners/operators, engine manufacturers, engine consultants and SoCalGas, formed specifically to provide input to staff during the Rule 1110.2 amendment process. The demonstration program, which was carried out on rich-burn, natural gas-fired engines consisted of two tasks:

Task 1 -	Emission compliance was evaluated for six existing engines with typical air/fuel ratio controllers (AFRCs) via weekly NOx and CO emission checks over a three-month period.
Task 2 -	The latest models of AFRCs from four manufacturers were retrofitted to existing engines, and each system was evaluated for approximately one week based on continuous NOx and CO emission monitoring.

The two tasks are documented in two reports (References Nos. ??? and ???). The Principal Investigators were Dan McGivney of Eastern Municipal Water District (EMWD) for Task 1 and Gregg Arney of SoCalGas for Task 2. The reports were submitted to AQMD in final form without giving AQMD any opportunity to review or comment on the reports.

Task 1 – Typical Air/Fuel Ratio Controllers

The six engines selected for Task 1 are listed in Table E-1. These engines were selected to represent a cross section of typical rich-burn, natural gas engines. Parameters that were considered in selecting the engines included BACT versus BARCT (i.e., Rule 1110.2) emission limits, AFRCs with partial-authority versus full-authority fuel valves, and AFRCs with pre-catalyst O2 sensors only versus those with both pre- and post-catalyst O2 sensors. The selected engines also spanned ranges of engine age and catalyst age.

Although the engines and emission controls for the engines are typical, the operator of the engines is not. All of the engines were located at facilities operated by Eastern Municipal Water District (EMWD). EMWD operates more than 70 ICEs at several wastewater treatment facilities in Riverside County. EMWD has experienced staff to maintain and operate the engines. Many of the engines are remotely and continuously monitored for problems with the engines and the control equipment. EMWD engines represent the best-case for a project of this type.

The Task 1 evaluation period commenced on November 28, 2005 and ran until February 21, 2006. Prior to the start of the weekly emission checks, the engines were given any needed maintenance, new O2 sensors were installed and the O2 sensor millivolt targets were adjusted to bring NOx and CO into compliance based on portable analyzer readings. During the three-month evaluation period, NOx and CO emissions from each engine were checked weekly by an independent testing firm using a portable analyzer. Engine and AFRC data were recorded daily and at the time of each emission check. The recorded data included the engine-hours, fuel flow

Table E-1. Task 1 Engines

AQMD Appl. No.	EMWD Engine No.	NOx/CO Limits, ppmvd @ 15% O2	Caterpillar Model No.	Engine Size, hp	Engine Hours at Start of Program	AFRC Make, Model	AFRC Fuel Authority	Post-Catalyst O2 Sensor (EGO3)?	Catalyst Manufacturer	No. of Catalyst Elements	Catalyst Hours at Start of Program
393971	8	52/2000	3306NA	145	12,624	Miratech MEC 2001	Partial	Yes	Miratech	2	324
411024	16	45/2000	G342-SI-NA-HCR	225	6,367	Altronic EPC 100	Partial	No	Houston Industrial	2	12,305
443610	86	12/76	3306NA	145	26,109	Altronic EPC 100	Partial	No	GT Exhaust	1	867
447147	92	59/2000	G398-SI-NA-HCR	500	45,688	Altronic EPC 100	Partial	No	Houston Industrial	2	3,812
436931	101	52/2000	3306NA	145	6,244	Miratech MEC 2001	Partial	Yes	Miratech	2	11,035
425052	187	12/76	G3508	310	1,622	Compliance Controls MEC-R	Full	Yes	Clean Air Power	2	1,422

rate, exhaust temperature, catalyst inlet and outlet temperatures, O2 sensor targets, O2 sensor millivolt readings, and any alarms. As an added check on the emissions, AQMD's Compliance department conducted several unannounced emission checks on the engines during the three-month period.

The report found that out of 89 emission tests conducted by the contractor and AQMD, 8 tests showed emission exceedances, for a non-compliance rate of 9%. The report also concluded that the AFRCs were unable to detect the emission exceedances and signal an alarm.

Table E-2 presents a summary of an AQMD analysis of the Task 1 results. Of greatest interest was the length of time that an engine could remain in compliance with its emission limits without any human intervention other than responding to alarms produced by the engine's emission control system. In making this determination based on the Task 1 data, a "mean time between failures" (MTBF) was computed for each engine. For this purpose, a "failure" was considered to have occurred whenever the engine was found exceeding its NOx or CO limit or whenever the O2 sensor target was changed other than in response to an alarm. In interpreting the data,

Table E-2. Summary of Task 1 Results

EMWD Engine No.	Load Range, %	On-Line Factor during Test Period	Operation during Test Period, Eng.-Hrs	Alarms Acted Upon during Test Period	Non-Alarm ECS* Mntnc or Adjustmt	Emission Exceed-ances	Mean Time between Failures (Eng-Hrs)
8	32-66	55%	1,126	0	1	0	923
16	93-116	83%	1,696	3	3	3	519
86	47-62	31%	627	0	2	1	209
92	54-80	91%	1,850	2	11	1	153
101	39-61	100%	2,030	1	1	0	1015
187	109-114	97%	1,984	0	1	2	671
				Wt'd Avg, All Engines			615
				Wt'd Avg, Engines w/ EGO3			862
				Wt'd Avg, Engines w/o EGO3			310

*ECS = emission control system

apparent target changes that appeared likely to be data errors were excused. The MTBF's for the six engines ranged from 153 to 1015 hours, with an average of 615 hours. This result suggests that the frequency at which well-maintained engines with typical AFRCs need to be checked is in the range of weekly to monthly.

The Task 1 results also suggested that AFRCs with both pre- and post-catalyst O2 sensors perform better than those with pre-catalyst O2 sensors only. The three engines with post-catalyst O2 sensors had an average MTBF of 862 hours versus 310 hours for the three engines without post-catalyst O2 sensors.

Task 2 – Modern Air/Fuel Ratio Controllers

Task 2 investigated the abilities of the latest models of AFRCs to maintain engines in compliance and detect non-compliance by retrofitting four such systems to existing engines and monitoring the NOx and CO emissions for a period of approximately one week in each case.

<u>AFRCs Tested</u>

Table E-3 lists the four AFRCs that were tested and some significant features of each. All four of these AFRCs are microprocessor-based and have the following alarm capabilities: catalyst temperature too high or too low, fuel valve at rich or lean limit, O2 sensor fault. The test periods and engine on which each test took place are also listed in the table.

Table E-3. Advanced Air/Fuel Ratio Controllers Tested

Make	Model	Post-Catalyst O2 Sensor	Heated O2 Sensor(s)	Fuel Authority	Target-vs.-Load Map Capability	Test Period (2006)	Engine No.
Continental Controls	ECV5	No	No	Full	No	Feb 9 – Feb 19	128
Altronic	EPC-100	No	No	Full	No	Feb 23 – Mar 7	128
Woodward	GECO	Yes	Post-Catalyst	Partial	Yes	Mar 9 – Mar 15	128
Miratech/ Compliance Controls	MEC-R	Yes	Pre- and Post-Catalyst	Full	Yes	Mar 28 – April 12	128
Miratech/ Compliance Controls	MEC-R	Yes	Pre- and Post-Catalyst	Full	Yes	June 8 – June 20	187

<u>Test Engines</u>

As indicated in Table E-3, the four AFRCs were installed and tested sequentially on Engine No. 128 during February-April 2006, and one AFRC was tested again in June 2006 on Engine No. 187. Engine No. 128 is located at EMWD's Perris treatment facility. This engine (AQMD

Application No. 411023, Caterpillar Model No. G342-SINA-HCR) is a 225 hp blower engine, which normally operates at steady load. It is equipped with a two-element Houston Industrial catalyst (Model No. DN/S 2605 H), sized to meet Rule 1110.2 NOx and CO limits of 57 (efficiency-corrected) and 2000 ppmvd @ 15% O2, respectively. Engine No. 187 is one of the Task 1 engines (Table HBL2-1). This is also a steady-load engine. Both engines have a diurnal fuel flow variation with a total range of less than 10%.

Results and Conclusions

Because the emissions from Engine 128 were so poor with three of the four AFRCs tested, the Stakeholders' official report (Reference 9) did not even include the data for those three AFRCs. The report declared those results as inconclusive and blamed the poor performance on several factors. First, they initially adjusted the AFRCs to achieve the lowest simultaneous NOx and CO emissions, which were better than current BACT levels even though the Engine 128 catalyst was only designed to achieve Rule 1110.2 BARCT levels. Second, not enough time was available to properly set up each AFRC. And third, they determined after the tests that the reference method CO analyzer had a positive interference from nitrous oxide[24] (N_2O) which means the CO emissions were less than reported by the analyzer. The report only includes data for the one Altronic AFRC on Engine 128 that achieved the best results.

A follow-up evaluation of the Compliance Controls MEC-R AFRC on Engine No. 187, which has a catalyst designed to achieve BACT levels, was performed in hopes of achieving better results than with Engine 128. Results of this test are reported.

Despite the withholding of much of the data, the report draws several conclusions:

1. None of the tested AFRCs were able to consistently keep the engine emissions in compliance, with engine load variations being particularly troublesome.
2. Proper programming of control parameters on each engine-AFRC system was difficult and time consuming.
3. Although modern AFRCs can detect and alarm for certain conditions, such as a faulty O2 sensors, exhaust temperatures that are too low or too high, and fuel valves reaching their rich or lean limits, they could not detect gradual increase of emissions, in the course of a week, to non-compliant levels.
4. AFRCs need to adopt more complex monitoring and control algorithms to detect excess emissions. One possible important parameter identified was the dithering of the oxygen sensor voltage, measured by the standard deviation of the signal.

The report also recommends that rule amendments encourage AFRC advancements by allowed reduced monitoring and emission testing if operators demonstrate their AFRC is capable of detecting excess emission.

[24] N_2O, also known as laughing gas, is not considered as NOx or measured as NOx by the reference methods. N_2O is a significant greenhouse gas since it about 275 times more potent than carbon dioxide. There is evidence that the TWCs on rich-burn engines generate N_2O when they operate too rich.

Reported Engine 128 Results

The Altronic AFRC, after initial setup March 21-22, performed fairly well over a 11-day period of CEMS NOx and CO monitoring (February 23 – March 6). The results are shown in Figure E-1, where both the NOx and CO uncorrected concentrations (about 0% O2) in ppmvd are reported. Although the engine permit limits are 202 ppmvd NOx and 7080 ppmvd CO, uncorrected, based on Rule 1110.2, the engine was initially tuned to lowest possible emissions which met BACT levels of approximately 38 ppmvd NOx and 245 ppmvd CO, uncorrected. Except for some NOx spikes on March 24 (presumably from lower than normal loads during reported engine mapping engine), emissions met BACT levels until March 28 when NOx went out of control and the AFRC set point had to be readjusted. By March 4 the NOx again drifted to above BACT levels. There were also NOx spikes on March 2 and March 3. There were unexplained steady increases of NOx and CO together that imply that periodic testing and AFRC readjustment is needed.

Reported Engine 187 (Well 36) Results

The Miratech MEC-R AFRC, when tested on Engine No. 187, also performed well for nine days until a problem occurred (Figure E-2). Setup was completed June 8, and NOx and CO were monitored for the following ten days. Both pollutants were in compliance with BACT permit limits (42 ppm NOx and 269 ppm CO, uncorrected) during the first nine days. In the tenth day (June 18), the AFRC appeared to lose control, with NOx declining and CO climbing sharply upward and slightly exceeding the permit limit by the end of the day. This is typical of an engine operating too rich. In artificial load-variation tests on June 19, reduction of load by about 20% brought CO back into compliance while NOx remained in compliance; and restoration to full load caused CO to return to its high level in exceedance of the permit limit.

Figure E-1. 15-Min. Avg. NOx and CO (Uncorrected)
for Altronic EPC-100 on Engine No. 128

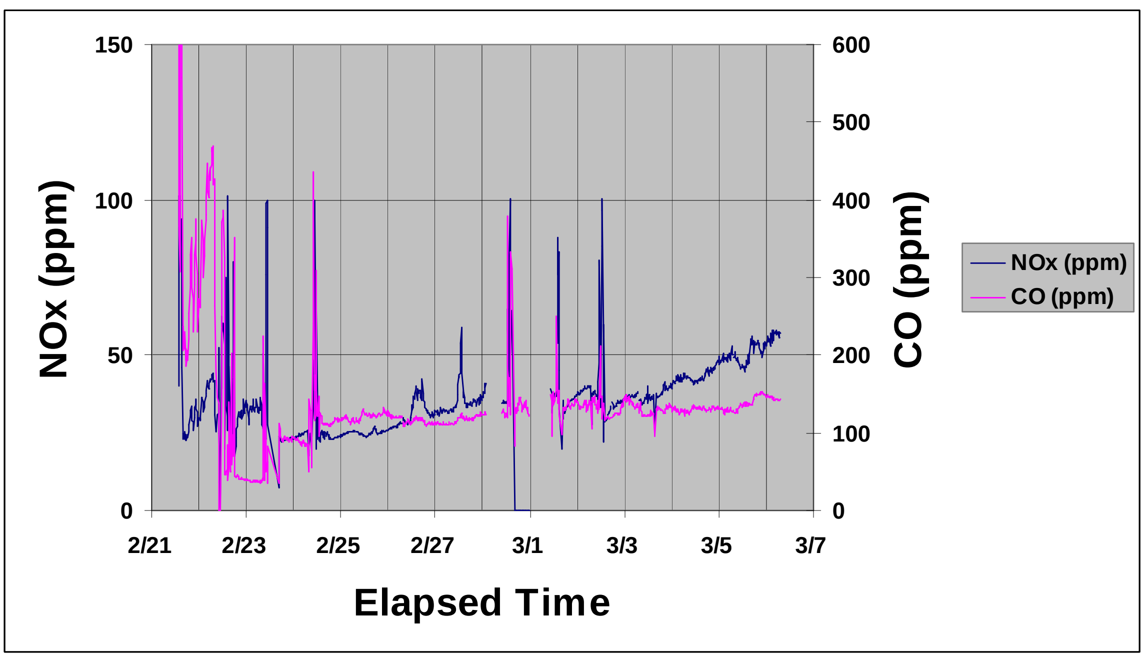
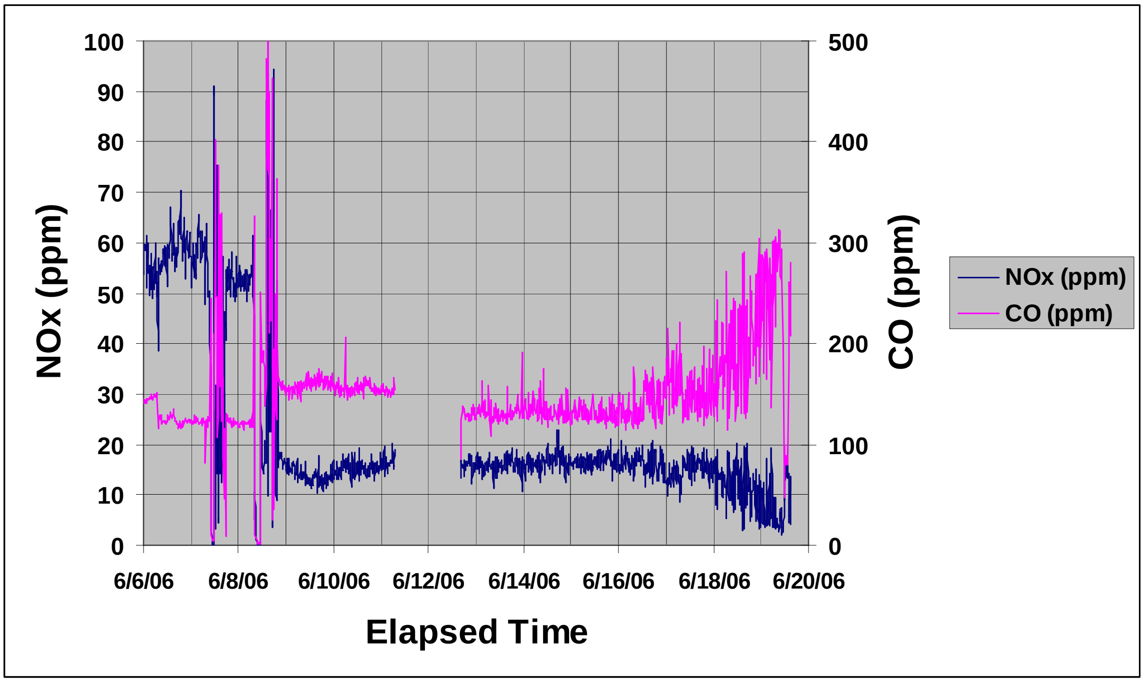


Figure E-2. 15-Min. Avg. NOx and CO (Uncorrected) for Miratech/Compliance Controls MEC-R on Engine No. 187



Unpublished Results

Besides not publishing results for three of the five tests, the Stakeholder Task 2 report had another drawback. The NOx monitor had a maximum range of only 100 ppmvd, uncorrected (about 29 ppmvd @ 15% O2). Although the monitor was capable of measuring NOx that exceeded BACT levels, it was not capable of measuring NOx that exceeded the Rule 1110.2 NOx limit of 57 ppmvd @ 15% O2 (about 202 ppmvd uncorrected).

However, AQMD had a contract with Advanced Engine Technologies Corporation, the Task 2 emission testing contractor, to do another project simultaneously with the Task 2. This involved testing the Task 2 engine 128 with a low-cost, semi-continuous, electrochemical cell NOx/CO analyzer, normally used a portable analyzer, side-by-side with the Task 2 CEMS package. The electrochemical cell analyzer was able to measure NOx emissions over 100 ppmvd uncorrected. In order to extend the life of the electrochemical cells, NOx emissions were only measured for one 15-minute period each hour. Therefore, it may have missed some short-term exceedances that the CEMS would catch.

The following four Figures E-3 through E-6 show the NOx and CO emission data from the electrochemical analyzer for the tests with each of the four AFRCs tested on Engine No. 128. Unlike the previous figures, these show emissions concentrations corrected to 15% O2, for easier comparison to BACT and Rule 1110.2 limits. Also shown is the 57 ppmvd Rule 1110.2 NOx limit (15% O2). The previous figure for this engine only showed peak NOx levels of 29 ppm @ 15% O2 (100 ppm uncorrected), within the Rule 1110.2 limit, while the electrochemical analyzer data show that all four AFRCs had exceedances of 57 ppmvd @ 15% O2 Rule 1110.2 limit. The two highest exceedances were 460 ppmvd and 532 ppmvd.

Figure E-3. Electrochemical Analyzer Data for the Woodward GECO AFRC on Engine No. 128

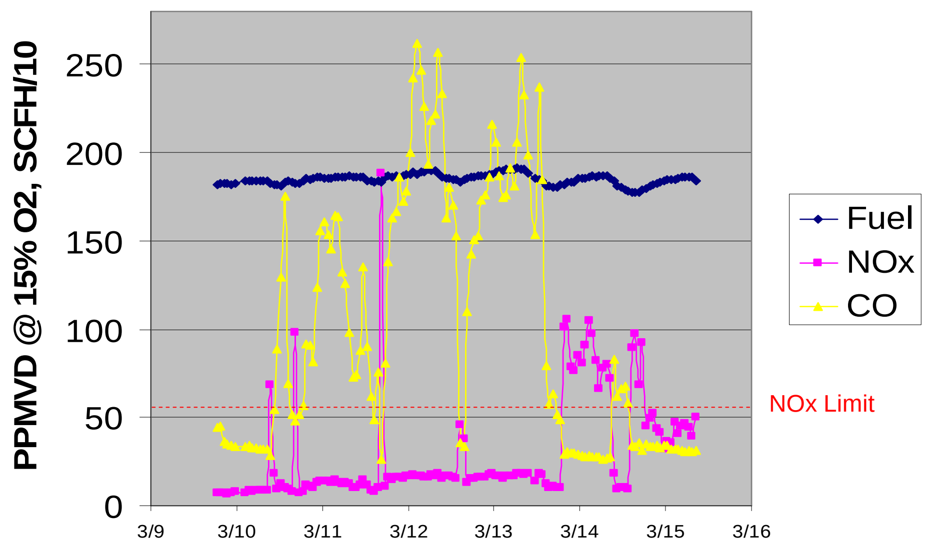


Figure E-4. Electrochemical Analyzer Data for the Continental AFRC on Engine No. 128

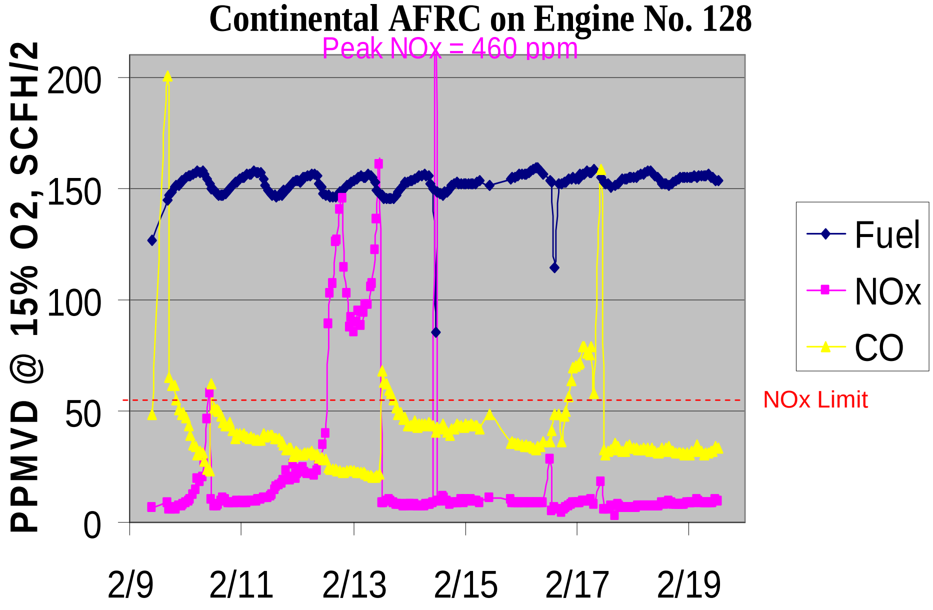


Figure E-5. Electrochemical Analyzer Data for the Compliance Controls MEC-R AFRC on Engine No. 128

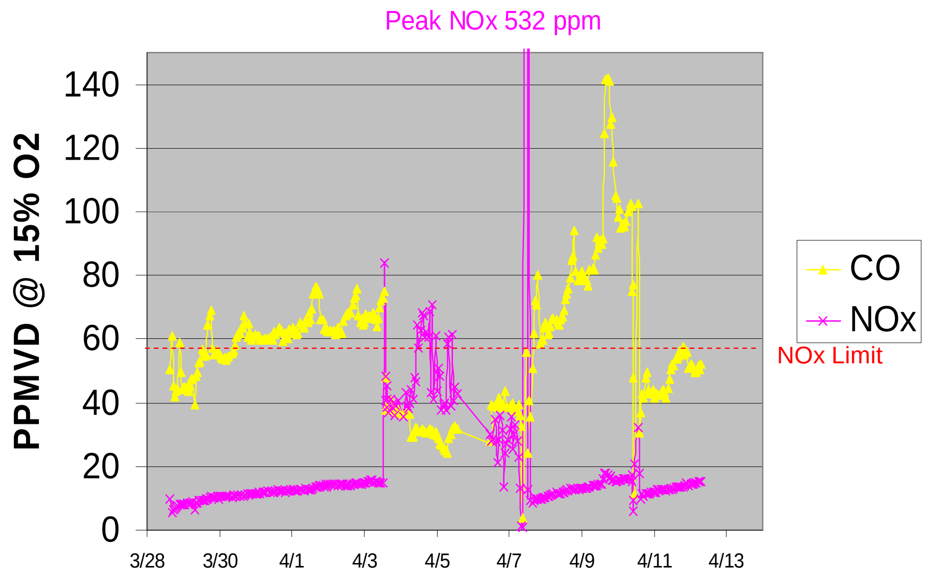
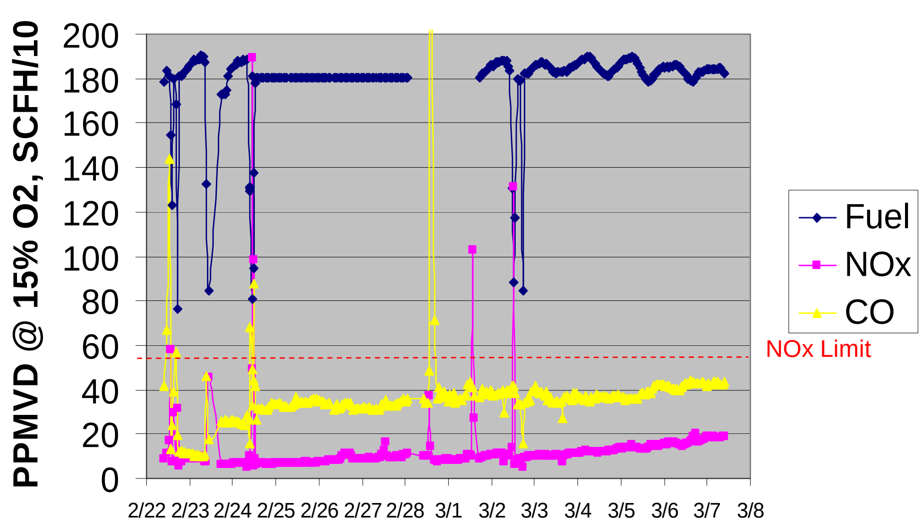


Figure E-6. Electrochemical Analyzer Data for the Altronic EPC-100 AFRC on Engine No. 128



APPENDIX F

Comparative Analysis Tables

Table F-1 - Comparison of Key Elements of the Federal RICE NESHAP and PAR 1110.2 that Are Applicable to SI and CI Engines

General Requirements	**Reciprocating Internal Combustion Engine (RICE) NESHAP**	**PAR 1110.2**
Applicability	Applies to stationary CI and SI engines above 500 HP located at a major source[25] throughout the U.S.	Applies to stationary and portable CI and SI engines above 50 hp located in the SCAQMD
Targeted Pollutants	Formaldehyde and CO[26]	NO_x, VOCs, and CO
Exemptions	New or reconstructed[27] RICE meeting any of the following criteria have no requirements except for an initial notification (within 120 days of publication of final rule in Federal Register) • Emergency power • Those that operate < 50 hrs/yr • Uses digester or landfill gas The following existing[28] RICE: • SI two-stroke, lean-burn (2SLB) • SI four-stroke, lean-burn (4SLB) • CI • Emergency • Those that operate < 50 hrs/yr • Those that use digester or landfill gas RICE being tested at test	• Portable engines registered under the state registration program. • Emergency standby engines which operate ≤ 200 hours per year and engines powering orchard wind machines. • Engines used for: fire-fighting and flood control; research and testing; performance and testing verification; powering other engines or gas turbines during start-ups. • Engines operating on San Clemente Island and in the Eastern portion of Riverside County, outside the non-attainment areas. • Supplemental engines which only operate from November 1 to April 15 for making snow or operating ski lifts.

[25] A major source of Hazardous Air Pollutants (HAP) is a plant site that emits or has the potential to emit any single HAP at a rate of 10 tons or more per year or any combination of HAP at a rate of 25 tons or more per year. Although numerous HAP may be emitted from engines, formaldehyde, acrolein, methanol, and acetaldehyde account for essentially all of the HAP mass emissions.

[26] EPA considers CO to be a surrogate for all of the organic HAPs.

[27] New RICE if construction began on or after 12/19/02. Reconstructed RICE if reconstruction began on or after 12/19/02.

[28] Existing RICE if construction or reconstruction began before 12/19/02.

<table>
<tr><td></td><td>cells/stands.</td><td></td></tr>
<tr><td>Emission Limits</td><td>Existing, new and reconstructed SI four-stroke, rich-burn, (4SRB) stationary RICE:
• Reduce formaldehyde by 76% or more. If construction or reconstruction began between 12/19/02 and 6/15/04, may reduce by 75% or more until 6/15/07; or
• Limit concentration of formaldehyde to 0.35 ppmvd or less @15% oxygen

New and reconstructed lean-burn and CI stationary engines

2SLB
• Reduce CO by 58% or more; or
• Limit formaldehyde to 12 ppmvd or less @15% oxygen. If construction or reconstruction began between 12/19/02 and 6/15/04 may reduce to 17ppmvd or less until 6/15/07.

4SLB
• Reduce CO by 93% or more ; or
• Limit formaldehyde to 14 ppmvd or less @15% oxygen.

CI Engine
• Reduce CO by 70% or more; or
• Limit formaldehyde to 0.58 ppmvd or less @15% oxygen.</td><td>Stationary engines with an Approved Emission Control Plan to electrify, but later chose not: 11 ppm NOx, 30 ppm VOC and 70 ppm CO at 15% oxygen dry basis.

Engines used in the following applications:
• New Non-Emergency Electric power generation
0.07 lbs/MW-hr NOx
0.01 lbs/MW-hr CO
0.02 lbs/MW-hr VOC
• Biogas-fired, >90%
<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td><500 hp 45**
≥ 500 hp: 36**</td><td>landfill gas: 40
digestor gas: 250**</td><td>2000</td></tr>
</table>

<u>Effective 7/1/12:</u>
<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td>11</td><td>30</td><td>70</td></tr>
</table>

All other engines:
<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td><500 hp 45
≥ 500 hp: 36</td><td>250</td><td>2000</td></tr>
</table>

<u>Effective 7/1/10:</u>
<table>
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<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td><500 hp 45</td><td>250</td><td>2000</td></tr>
<tr><td>≥ 500 hp: 11</td><td>30</td><td>70</td></tr>
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<tr>
<td></td>
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<td>Effective 7/1/11:

<table>
<tr><td colspan="3">Concentration Limits, ppm*</td></tr>
<tr><td>NOx</td><td>VOC</td><td>CO</td></tr>
<tr><td>11</td><td>30</td><td>70</td></tr>
</table>
*Corrected to 15% O2 and averaged over 15 minutes for NOx/CO and 30 minutes for VOC
**Allowed an efficiency correction if >25%</td>
</tr>
<tr>
<td>Operating Limitations</td>
<td>Existing, new and reconstructed 4SRB stationary RICE:
If complying with formaldehyde reduction requirements using oxidation catalyst (OC):
• Limit OC pressure drop to <2 in. w.c increase from initial test and maintain OC inlet temperature inlet to ≥750°F.

If complying with formaldehyde reduction requirements and not using an OC:
• Operation limits approved by EPA Administrator.

New and reconstructed lean-burn and CI stationary RICE:

If complying with CO reduction requirements or formaldehyde reduction requirements using an OC:
• Limit OC pressure drop to <2 in. w.c increase from initial test and maintain OC inlet temperature inlet to ≥450°F and ≤1350°F.</td>
<td>Portable Engines:

Not allowed for power production into the electric grid except during emergency.</td>
</tr>
</table>

	If complying with CO reduction requirements or formaldehyde reduction requirements without OC: • Operation limits approved by EPA	
Testing and Monitoring	An initial source test of all subject RICE units Stationary 2SLB, 4SLB and CI engines complying with CO limits: • Semi-annual testing of CO (and O2) % reduction across catalyst. • If using OC and continuous parameter monitoring system (CPMS), measure the pressure drop and inlet temperature of catalytic oxidizer and maintain 4-hour rolling averages within OC inlet temperature operating limits established during performance test. • If not using OC, use CPMS to monitor and record operating parameters approved by EPA and maintain 4-hour rolling averages of operating parameters within limits established during performance test. • If using CEMS, measure CO (and O2 or CO2) continuously at inlet and outlet of OC and demonstrate CO reduction by 4-hour averaging period. Conduct annual relative accuracy test audit (RATA) of CEMS. 4SRB engines complying with formaldehyde limits:	<u>Testing</u> All stationary engines: • Non-resettable totalizing time meter. • Conduct a NOx, VOC and CO source test once every 2 years or every 8,760 operating hours, whichever occurs first. <u>CEMS</u> Engines ≥1000 bhp and operating >two million bhp-hr per calendar year: CEMS for continuous NOx and CO monitoring. On and after 7/1/08 facilities with engines having combined rating of ≥1000 bhp at the same location and combined fuel usage >16 x 10^9 Btu/year: CEMS for continuous NOx and CO monitoring. CEMS may be time shared by multiple engines. An alternative monitoring device may be installed upon approval by the Executive Officer. <u>Inspection and Monitoring (I&M) Plan</u> For engines without CEMS, establish operating limits of the following: • Engine load • Oxygen sensor voltage output or equivalence ratio (phi)

	• Measure formaldehyde at 15% O2, oxygen and moisture at inlet and outlet of control device. • If using NSCR, use CPMS to measure the pressure drop and inlet temperature of catalyst and maintain 4-hour rolling averages within operating limits of catalyst inlet temperature • If not using NSCR, use CPMS to monitor operating parameters approved by EPA and maintain 4-hour rolling averages of parameters within operating limits established during performance test. • If bhp ≥5,000, conduct semiannual tests to demonstrate compliance with formaldehyde limits. All RICE complying with formaldehyde limits: • Semiannual testing of formaldehyde. • If using OC or NSCR, record pressure drop monthly and use CPMS to measure catalyst inlet temperature; maintain 4-hour rolling averages within operating limits • If not using OC or NSCR, use CPMS to monitor operating parameters approved by EPA and approved parameters from initial performance test and maintain 4-hour rolling averages of operating limits established during performance test .	• Catalyst inlet/outlet temperatures • Reactant (ammonia or urea) flow rate for lean-burn engines with selective catalytic control devices Malfunction light and audible alarm Every week or 150 engine operating hours use portable analyzer for NOx, CO and O2 emission checks. Daily monitoring of: • Operating hours • Oxygen sensor voltage output or equivalent ratio (phi) deviation • Faults and/or alarms Rich-Burn engine: • Oxygen sensor set point • Use portable analyzer to establish oxygen sensor range. New Non-Emergency Electrical Generating Engines: • Net Electrical output • Daily and Annual heat recovered (MW-hrs) for CHP systems

Recordkeeping and Reporting	Keep comprehensive records supporting compliance with all applicable provisions of the RICE NESHAP. Records must be in a form suitable and readily available for expeditious review and be kept for 5 years.	<u>Recordkeeping:</u> Keep all test reports and logs required by rule for 5 years, including: Monthly engine log of: • Total hours of operation • Type of fuel used • Fuel consumption • Cumulative hours of operation since last source test, for stationary engines only. Records of all parameters and actions required by the I&M Plan <u>New Non-Emergency Electrical Generating Engines:</u> • Net Electrical output • NOx, CO and VOC (lbs/MW-hr) • Daily and Annual heat recovered (MW-hrs) for CHP systems <u>Reporting</u> Engine noncompliance and breakdowns

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Table F-2 - Comparison of Key Elements of the Federal Stationary Compression-Ignition Engine New Source Performance Standards (CIE NSPS) and PAR 1110.2

General Requirements	**CIE NSPS**	**PAR 1110.2**
Applicability	Operators: New, modified or reconstructed stationary CIEs after 7/11/2005 in USA Manufacturers: Model year 2007 and later stationary CI engines	Stationary and portable CI and SI engines above 50 hp located in the SCAQMD
Targeted Pollutants	NOx, PM, CO, and NMHC	NO_x, VOCs, and CO
Exemptions	Operators: • CIEs manufactured before 4/1/2006 • Fire pumps manufactured before 7/1/2006 and certified by the National Fire Protection Association (NFPA) • CIE Test Cells • Qualify for use in national security Manufacturers: • CIEs > 30 liters per cylinder Fire Pump CIE Model Years: • Pre 2011 HP<100 • Pre 2010 100≤HP<175 • Pre 2009 175≤HP≤750 • Pre 2008 HP>750	• Portable engines registered under the state registration program. • Emergency standby engines which operate ≤ 200 hours per year and engines powering orchard wind machines. • Engines used for: fire-fighting and flood control; research and testing; performance and testing verification; powering other engines or gas turbines during start-ups. • Engines operating on San Clemente Island and in the Eastern portion of Riverside County, outside the nonattainment areas. • Supplemental engines which only operate from November 1 to April 15 for making snow or operating ski lifts.
Emission Limits	Manufacturers of Non-Emergency CIEs • Model Year 2007 and later CIEs <30 liters/cylinder must be certified to comply with nonroad or marine standards of 40CFR89, 40CFR94 or 40CFR1039, except that Model Year 2007-2010 CIEs <3000 hp	Stationary engines with an Approved Emission Control Plan to electrify, but later chose not: 11 ppm NOx, 30 ppm VOC and 70 ppm CO at 15% oxygen dry basis. Engines used in the following applications: • New Non-Emergency

<table>
<tr>
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and <10 liters/cylinder must certify to Table F-3 limits. Averaging, banking and trading may be allowed.
<u>Operators of Non-Emergency CIEs</u>
Pre-2007 Model Years:

Table F-3 standards for < 10 liters/cylinder
40CFR94.8(a)(1) for ≥ 10 and < 30 liters cylinder

2007 and Later Model Years:

A CIE certified by the manufacturer for < 30 liters/cylinder

CIEs ≥ 30 liters cylinder:

NOx: ≥ 90% reduction or ≤ 1.2 g/hp-hr
PM: ≥ 60% reduction or ≤ 0.11 g/hp-hr

<u>Manufacturers of Emergency CIEs</u>
Model Year 2007 and later CIEs < 30 liters/cylinder must be certified to comply with nonroad or marine standards of 40CFR89, 40CFR94 or 40CFR1039, except that:

Only > 50 hp CIEs must comply with 40CFR1039 (Tier 4)
Model Year 2007-2010 CIEs < 3000 hp and < 10 liters/cylinder must certify to Table F-3 standards
Fire pump CIEs must be certified to Table F-4 standards starting in models years: 2011 for <100 hp; 2010 for ≥100 hp and <175 hp; 2009 for ≥175 hp and <750 hp; and 2008 for >750 hp

<u>Operators of Emergency CIEs</u>
</td>
<td>
Electric power generation
0.07 lbs/MW-hr NOx
0.01 lbs/MW-hr CO
0.02 lbs/MW-hr VOC

Biogas-fired, >90%

<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td><500 hp
45**
≥ 500 hp:
36**</td><td>landfill gas:
40
digestor gas:
250**</td><td>2000</td></tr>
</table>
<u>Effective 7/1/12:</u>
<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td>11</td><td>30</td><td>70</td></tr>
</table>
All other engines:
<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td><500 hp
45
≥ 500 hp:
36</td><td>250</td><td>2000</td></tr>
</table>
<u>Effective 7/1/10:</u>
<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td><500 hp
45
≥ 500 hp:
11</td><td>250

30</td><td>2000

70</td></tr>
</table>
<u>Effective 7/1/11:</u>
<table>
<tr><th colspan="3">Concentration Limits, ppm*</th></tr>
<tr><th>NOx</th><th>VOC</th><th>CO</th></tr>
<tr><td>11</td><td>30</td><td>70</td></tr>
</table>
*Corrected to 15% O2 and averaged over 15 minutes for NOx/CO and 30 minutes for VOC
**Allowed an efficiency correction if >25%
</td>
</tr>
</table>

	Must comply with same requirements as non-emergency engines, except fire pump CIEs must comply with Table F-4 standards	
Operating Limitations	• Diesel fuel sulfur content limits: 500 ppm by 1/1/2010; for <30 liters/cylinder, 15 ppm by 10/1/2010 • Operate and maintain the CIE per manufacturer's written instructions and per applicable 40CFR Parts 89, 94 and 1039 • For emergency CIEs, readiness testing and maintenance checks limited to 100 hours/year	Portable Engines: Not allowed for power production into the electric grid except during emergency.
Testing and Monitoring	<u>Operators</u> • Non-resettable hour meter for emergency CI engines • Backpressure monitor for diesel particulate filters • For uncertified pre-2007 CIEs, an initial source test of the CIE, or records of a test of a similar engine, manufacturer data, or control equipment vendor data • For CIEs >30 liters/cylinder, an initial source test, annual source tests for non-emergency CIEs, and continuous monitoring of operating parameter approved by EPA. • Source test procedures: In-use procedures of 40CFR1039; or, for >30 liters/cylinder CIEs, specified 40CFR60 methods. <u>Manufacturers</u> Certification testing required	<u>Testing</u> All stationary engines: • Non-resettable totalizing time meter. • Conduct a NOx, VOC and CO source test once every 2 years or every 8,760 operating hours, whichever occurs first. <u>CEMS</u> Engines ≥1000 bhp and operating >two million bhp-hr per calendar year: CEMS for continuous NOx and CO monitoring. On and after 7/1/08 facilities with engines having combined rating of ≥1000 bhp at the same location and combined fuel usage >16 x 10^9 Btu/year: CEMS for continuous NOx and CO monitoring. CEMS may be time shared by multiple engines. An alternative monitoring device may be installed upon

	by 40CFR89 or 40CFR94 or 40CFR1039	approval by the Executive Officer. <u>Inspection and Monitoring (I&M) Plan</u> For engines without CEMS, establish operating limits of the following: • Engine load • Oxygen sensor voltage output or equivalence ratio (phi) • Catalyst inlet/outlet temperatures • Reactant (ammonia or urea) flow rate for lean-burn engines with selective catalytic control devices Malfunction light and audible alarm Every week or 150 engine operating hours use portable analyzer for NOx, CO and O2 emission checks. Daily monitoring of: • Operating hours • Oxygen sensor voltage output or equivalent ratio (phi) deviation • Faults and/or alarms Rich-Burn engine: • Oxygen sensor set point • Use portable analyzer to establish oxygen sensor range. New Non-Emergency Electrical Generating Engines: • Net Electrical output • Daily and Annual heat recovered (MW-hrs) for CHP systems

Recordkeeping and Reporting	Recordkeeping: • Records of maintenance, CIE certification, documentation of compliance for uncertified CIEs • For CIEs with diesel particulate filters, records of corrective actions when backpressure limits are exceeded. • For emergency CIEs, records of operating time and reasons for operation	Recordkeeping: Keep all test reports and logs required by rule for 5 years, including: Monthly engine log of: • Total hours of operation • Type of fuel used • Fuel consumption • Cumulative hours of operation since last source test, for stationary engines only. Records of all parameters and actions required by the I&M Plan New Non-Emergency Electrical Generating Engines: • Net Electrical output • NOx, CO and VOC (lbs/MW-hr) • Daily and Annual heat recovered (MW-hrs) for CHP systems Reporting Engine noncompliance and breakdowns

TABLE F-3 — EMISSION STANDARDS FOR STATIONARY PRE-2007 MODEL YEAR ENGINES WITH A DISPLACEMENT OF <10 LITERS PER CYLINDER AND 2007–2010 MODEL YEAR ENGINES >2,237 KW (3,000 HP) AND WITH A DISPLACEMENT OF <10 LITERS PER CYLINDER

Maximum engine power	Emission standards for stationary pre-2007 model year engines with a displacement of <10 liters per cylinder and 2007–2010 model year engines >2,237 KW (3,000 HP) and with a displacement of <10 liters per cylinder in g/KW-hr (g/HP-hr)				
	NMHC + NO_X	HC	NO_X	CO	PM
KW<8 (HP<11) .	10.5 (7.8)		....	8.0 (6.0)	1.0 (0.75)
8≤KW<19 (11≤HP<25)	9.5 (7.1)		....	6.6 (4.9)	0.80 (0.60)
19≤KW<37 (25≤HP<50)	9.5 (7.1)		....	5.5 (4.1)	0.80 (0.60)
37≤KW<56 (50≤HP<75)			9.2 (6.9)	....	....
56≤KW<75 (75≤HP<100)			9.2 (6.9)	....	....
75≤KW<130 (100≤HP<175)			9.2 (6.9)	....	....
130≤KW<225 (175≤HP<300)		1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)
225≤KW<450 (300≤HP<600)		1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)
450≤KW≤560 (600≤HP≤750)		1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)
KW>560 (HP>750)		1.3 (1.0)	9.2 (6.9)	11.4 (8.5)	0.54 (0.40)

TABLE F-4 —EMISSION STANDARDS FOR STATIONARY FIRE PUMP ENGINES

Maximum Engine Power	Model Year(s)	NMHC + NO_X	CO	PM
KW<8 (HP<11)	2010 and earlier	10.5 (7.8)	8.0 (6.0)	1.0 (0.75)
....	2011+	7.5 (5.6)	....	0.40 (0.30)
8≤KW<19 (11≤HP<25)	2010 and earlier	9.5 (7.1)	6.6 (4.9)	0.80 (0.60)
....	2011+	7.5 (5.6)	....	0.40 (0.30)
19≤KW<37 (25≤HP<50)	2010 and earlier	9.5 (7.1)	5.5 (4.1)	0.80 (0.60)
....	2011+	7.5 (5.6)	....	0.30 (0.22)
37≤KW<56 (50≤HP<75)	2010 and earlier	10.5 (7.8)	5.0 (3.7)	0.80 (0.60)
....	2011+ [1]	4.7 (3.5)	....	0.40 (0.30)
56≤KW<75 (75≤HP<100)	2010 and earlier	10.5 (7.8)	5.0 (3.7)	0.80 (0.60)
....	2011+ [1]	4.7 (3.5)	....	0.40 (0.30)
75≤KW<130 (100≤HP<175)	2009 and earlier	10.5 (7.8)	5.0 (3.7)	0.80 (0.60)
....	2010+ [2]	4.0 (3.0)		0.30 (0.22)
130≤KW<225 (175≤HP<300)	2008 and earlier	10.5 (7.8)	3.5 (2.6)	0.54 (0.40)
	2009+ [3]	4.0 (3.0)	....	0.20 (0.15)
225≤KW<450 (300≤HP<600)	2008 and earlier	10.5 (7.8)	3.5 (2.6)	0.54 (0.40)
....	2009+ [3]	4.0 (3.0)	....	0.20 (0.15)
450≤KW≤560 (600≤HP≤750)	2008 and earlier	10.5 (7.8)	3.5 (2.6)	0.54 (0.40)
....	2009+	4.0 (3.0)	....	0.20 (0.15)
KW>560 (HP>750)	2007 and earlier	10.5 (7.8)	3.5 (2.6)	0.54 (0.40)
....	2008+	6.4 (4.8)	....	0.20 (0.15)

[1] For model years 2011–2013, manufacturers, owners and operators of fire pump stationary CI ICE in this engine power category with a rated speed of greater than 2,650 revolutions per minute (rpm) may comply with the emission limitations for 2010 model year engines.

[2] For model years 2010–2012, manufacturers, owners and operators of fire pump stationary CI ICE in this engine power category with a rated speed of greater than 2,650 rpm may comply with the emission limitations for 2009 model year engines.

[3] In model years 2009–2011, manufacturers of fire pump stationary CI ICE in this engine power category with a rated speed of greater than 2,650 rpm may comply with the emission limitations for 2008 model year engines.